

Biofuel Policies and the Green Paradox

Emily S. Potter



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Preface

The topic of this thesis was inspired by research conducted during the summer of 2010 at Statistics Norway on the current status and future challenges of second generation biofuels and all of the subjects studied during my work towards obtaining an MS of Philosophy in Environmental and Developmental Economics, but most importantly, the field of resource economics.

I would like to express my deep gratitude to my supervisor, Mads Greaker, for his invaluable insight, guidance and feedback. I would also like to thank Bjart Holtsmark for the use of his climate change model and Lars Lindholt for his help in navigating the global transport energy market and thought provoking discussions.

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1 Introduction

Approximately 25% of all carbon dioxide-equivalent (CO₂e) emissions, or anthropogenic greenhouse gas (GHG) emissions, come from the transport sector, which relies on petroleum to supply the majority of its energy needs. According to the International Panel on Climate Change (IPCC), transport's GHG emissions have increased at a faster rate than any other energy using sector and emissions are expected to continue to grow at a rate of about 2% per year if the current energy usage patterns persist. Biofuels have been promoted as one possible and promising way of reducing GHG emissions from the transport sector and are the primary option for cutting transport fossil fuel energy use and emissions until electric and/or hydrogen fuel cell powered vehicles and supporting infrastructure can be deployed. Moreover, the technology is available today without reducing consumer utility of cars as opposed to hydrogen and battery driven cars. Growth of global biofuel production, a result of ambitious government support programs, and developments in the production of 2nd generation biofuels made from cellulosic biomass, has encouraged several governments to continue to rely on biofuels as a renewable source of energy for the transport sector. This is in spite of the polarity surrounding the characteristics of 1st generation biofuels stemming from mounting criticism of their high lifecycle GHG emissions and proposed contribution to rising food prices.

The promotion of renewable energy sources and 'demand reducing policies' intended to lower consumption of fossil fuels in order to mitigate emissions has recently met criticism from economists. A body of economic theory has recently developed showing that policies designed to reduce the use of carbon emitting and exhaustible fossil fuel resources, such as oil, may actually lead to an increase in their use and therefore speed up global warming. Hence the term 'green paradox.' This occurs when the suppliers of the exhaustible resources react to the policies by increasing current supply in anticipation of reduced future demand. Increasing supply is equivalent to increasing emissions. If climate considerations are the driving force behind policies designed to support the continued growth of the biofuel industry, policymakers should take heed and proceed with caution in order to avoid unintended consequences.

While the effects of taxes on fossil fuels and subsidies to cleaner energy substitutes has been studied by Gerlagh (2010), Grafton et al. (2010), Hoel (2008, 2010), Sinn (2009) and Withagen and van der Ploegh (2010), among others, most analyses are highly theoretical. Furthermore, to my knowledge, no one has attempted to analyze the possible supply side response to two of the dominant strategies adopted to promote the use of biofuels. This paper attempts to address whether or not the Renewable Fuel Standards (RFS) or blending mandate requirements implemented by the U.S. and EU, respectively, which call for increasing use of biofuels in the transport sector throughout the next decade, will induce oil resource owners to increase current extraction and supply of the resource and therefore increase current emissions. Further, GHG accumulation and resulting temperature effects are calculated to evaluate whether the policy actions actually speed up global warming. The problem is addressed using a simplified model of the global transport market for energy, provided solely by fossil-based fuels made from oil and biofuels. A climate change model translates emissions from the use of the fossil-based fuels to the accumulation of GHGs in the atmosphere and temperature implications. Both models are built in Microsoft Excel and the Solver tool is used to calculate the optimal resource price and extraction paths for the different scenarios.

In an attempt to move from the abstract to the concrete, I created a model that simulates the global demand for transport energy through the year 2250. Reference cases are created for two market structures, one where transport oil is supplied by a competitive group of oil resource owners and one in which the oil resource is supplied by a monopolist. These reference scenarios are then modified by the introduction of either a RFS or blending mandate policy, on a global scale, that introduces biofuels into the market to evaluate how the oil resource owners may adjust their extraction/supply. Alterations to the oil extraction paths are synonymous with changes in the transport sector's carbon emissions generated by the use of the oil. These emissions are inputted into a climate change model that determines how emissions translate into the accumulation of GHGs in the atmosphere which affects estimated increases in the global temperature.

The findings suggest that, with the exception of the introduction of a renewable fuel standard policy in a market where oil is supplied competitively, resource extraction rates and emissions are delayed compared to reference scenarios in the absence of biofuel policies and the green paradox does not hold. For all policy scenarios evaluated, the modified resource extraction and emissions paths have negligible impacts on the accumulation of greenhouse gases in the atmosphere. The results imply that the use of biofuels in the transport sector as a substitute for oil will play a trivial role in mitigating future increases in global temperatures and that the employment of renewable fuel standards and blending mandates will not speed up the rate of global warming. While the results offer interesting insight as to how oil resource owners may react to RFS and blending mandate type policies, it is important to acknowledge that the outcomes hinge heavily on the design of the models used to calculate these reactions.

The next chapter is intended to provide a background on biofuels, with a focus on 2nd generation. Chapter 3 presents the theory of exhaustible resources and Chapter 4 presents the concept of the green paradox. The reference model assumptions and results are explained in chapter 5 and the biofuel policies and their potential impact on the market for transport fuels are addressed in chapter 6. Chapter 7 summarizes the results and conclusions. All currency (\$) is presented in U.S. dollars.

2 Biofuels

Biofuels are the renewable fuel considered as the substitute energy source for oil in the transport sector. In order to frame the context within which the research question is addressed, this chapter briefly surveys the current status of the biofuel industry and the political climate surrounding their use. A particular emphasis is placed on 2nd generation biofuels, since they are expected to play a large role in meeting future biofuel targets.

2.1 Overview

Biofuels, including ethanol and biodiesel fossil fuel substitutes made from biomass, have been in use since the earliest internal combustion engines. In fact, one of the first prototypes of the diesel engine was designed to run on vegetable oil, and several of Henry Ford's early cars ran on bioethanol. The interest in biofuels was renewed as a result of the 1970s oil shocks and is flourishing today with government support motivated by several factors including energy security, climate change concerns and rural development. Moreover, it is common to distinguish between 1st and 2nd generation biofuels. While 1st generation biofuels are made from feedstock also suitable for use in human food production, e.g., corn and sugarcane, 2nd generation biofuels are made from cellulosic material not useable as a food source. These feedstocks include agriculture and forest residues (e.g., bagasse and wood residues), wastes (e.g., organic municipal solid waste) and energy crops (vegetative grasses and short rotation forest crops such as switch grass and poplar trees). According to IPCC (2007), biofuels have the potential to replace a substantial part of petroleum used in the transport sector if technologies using cellulosic biomass succeed.

There is a global consensus that severe consequences will occur if global concentrations of CO₂e exceed 450-550 parts per million (ppm) by 2050 (IPCC, 2007). Limiting atmospheric concentrations to these levels will give us a 50% chance of limiting the increase in average global temperature to 2°C above pre-industrial levels. An increase above this level increases the probability of severe consequences for almost half of the world's population through increased cases of hunger, malaria, flooding and water shortages (IPCC, 2007). The World Energy Outlook 2009 450 Scenario, which models future energy demand given a long-term CO₂ atmospheric

concentration of 450 ppm, projects biofuels to provide 9% (11.7 EJ) of the total transport fuel demand (126 EJ) in 2030 (IEA, 2010a). In the Blue Map Scenario of Energy Technology Perspectives 2008, which also models future energy demand under the same 450 ppm target, biofuels provide 26% (29 EJ) of total transportation fuel (112 EJ) in 2050, with 2nd generation biofuels accounting for roughly 90% of all biofuel (IEA, 2008b). More than half of the 2nd generation biofuel production in the Blue Map Scenario is projected to occur in non-OECD countries, with China and India accounting for 19% of the total production (IEA, 2010b). Clearly, 2nd generation biofuels are expected to play a significant role in fulfilling transport energy needs in order to prevent dangerous levels of climate change.

Despite significant cost improvements over the past several decades, with the exception of Brazil's sugarcane-based ethanol, 1st generation biofuels are not price competitive with fossil fuels without significant government support. Opportunities for additional production cost reductions are severely limited. Furthermore, feedstock commodity price increases and energy costs have both contributed to higher production costs of 1st generation biofuels from 2004 to 2007 (IEA, 2008a). Even with recent high petroleum prices and no carbon taxation, most U.S. and EU producers would not be able to operate without government subsidies (Eggert and Greaker, 2009). On the other hand, cellulosic biofuels are made from far from ripe technologies, particularly those made using a biochemical process (see Eggert et al. (2011) or IEA (2008a) for further discussion of conversion technologies), and current production costs are too high to make them competitive with 1st generation biofuels. However, proposed technological advances and more favorable characteristics compared to the 1st generation biofuels have placed a huge reliance on this next generation to fulfill renewable fuel goals within the transport energy sector.

Production costs for 2nd generation cellulosic biofuels are currently not competitive with 1st generation biofuels or gasoline. Advances to date have brought down the cost from \$1.61-2.00/liters of gasoline equivalent (lge¹) in the 1980s to a level where they can compete with ethanol from corn today, and future developments can potentially bring down costs all the way

¹ A liter of ethanol contains 0.66 liters of gasoline equivalent. A liter of biodiesel contains 0.89 liters of diesel equivalent.

to \$0.24/lge (Wyman, 2008). Current costs are hard to confirm due to the proprietary nature of the data and the array of feedstock and conversion technologies available. This is evident in the wide range of current cost estimates presented in the literature of \$0.80-1.97/lge. Different assumptions about the timing of cost reductions and feedstock cost predictions explain the variance in future cost estimates which range from \$0.24-0.60/lge. The cost reductions will be driven by a combination of research and development breakthroughs, technology learning and economies of scale. In comparison, if crude oil prices are at \$100/barrel (bbl), gasoline production costs are \$0.63/liter plus refining costs.²

In addition to economic considerations, competition for land and food as well as lifecycle GHG assessments have drawn much criticism towards 1st generation biofuels and a desire to fulfill targets for the use of the renewable fuel with 2nd generation biofuels. Cellulosic biomass used in the production of 2nd generation biofuels refers to plant biomass composed of cellulose, hemicelluloses and lignin. Cellulosic materials are abundant, estimated to make up roughly 60-90% of terrestrial biomass by weight (Pew Center, 2009). In addition to not competing with food resources to the extent of 1st generation feedstocks, cellulosic biomass feedstock may, to a much larger extent, be produced on marginal land or even be recovered from organic waste and similar residuals. This reduces the problem of threatening food security and destroying habitats when expanding land use to grow 2nd generation feedstocks. Furthermore, 2nd generation biofuels are thought to improve land-use efficiency (Larson, 2008) which refers to the level of transportation service that can be provided from a hectare of land. 2nd generation biofuels can provide an improvement of approximately 50% in land-use efficiency over sugar-based 1st generation biofuels and an improvement of up to 2.5 times over starch-based biofuels.

Expert assessments of the global potential for bioenergy production could reach 33-1,500 EJ in 2050 (IEA, 2010b), the equivalent of roughly 5-245 billion barrels of oil equivalent (boe). The higher-end of the range is based on a scenario with highly advanced and intensive agriculture that would allow for a large share of current agricultural land, roughly 72%, to be available for

² Detailed data about refining costs is not available, but may be anywhere from \$0.05-\$0.20+/liter.
<http://energyalmanac.ca.gov/gasoline/margins/index.html>

biomass cultivation. Bioenergy covers various sources of biomass, including forestry and agricultural residues, waste and dedicated energy crops, i.e., 2nd generation (cellulosic) biofuel feedstocks. These factors are important in determining the theoretical capacity of biofuels to fulfill transport energy needs and are particularly crucial to support assumptions used to determine the supply of biofuels in the policy analyses which follow.

With regards to GHG emissions, recent contributions have directly questioned whether 1st generation biofuels actually lead to any short-run CO₂ reductions. Sources of emissions include the use of fertilizer when growing the 1st generation biofuel crops, the use of fossil energy in the harvesting and processing of the biofuels and land use change, including deforestation, among others. Land use change can lead to GHG emissions if the area of arable land is increased to accommodate growth of crop inputs for the production of biofuels.

Table 2.1: GHG reduction by biofuel type including indirect effects

<i>Biofuel type</i>	<i>30 year, 0% discount rate</i>
Corn ethanol (best case)	-26%
Corn ethanol (worst case)	+34%
Soy-based biodiesel	+4%
Sugarcane ethanol	-26%
Switchgrass ethanol (cellulosic)	-124%

Table 2.1 summarizes the GHG-reducing effect of different biofuels based on lifecycle analyses. As shown, cellulosic ethanol is by far the most promising biofuel to reduce emissions (EPA, 2009). Other studies have placed cellulosic biofuel emissions at 60-120% less than traditional fossil-based fuels, with the high end occurring if by-products of the biofuel conversion process are used for heating and electricity. In order to evaluate the climate impacts of certain biofuel policies, we assume that the net GHG contribution of biofuels is zero. This may be an aggressive assumption for earlier periods analyzed, but not so far from reality given that future growth in biofuel consumption is expected to come primarily from the 2nd generation or cellulosic-based biofuels.

Even though conversion technologies for the production of 2nd generation biofuels are thought to be promising, there is still great uncertainty as to whether production costs will come down and whether the availability of raw materials will be adequate for large-scale production to

fulfill the transports sector's energy demands. Thus, policies, preferably in the form of R&D investment and learning subsidies for cellulosic biofuels, should aim to uncover the technology's true potential and not operate with ambitious goals for the technology's future market penetration. Nevertheless, significant players in the biofuel market, the U.S. and EU in particular, have adopted policies that promote just that in the form of renewable fuel standards and blending mandates which guarantee a market for biofuels. These are used in combination with substantial direct subsidies to biofuel producers in the form of tax credits and discussed in more detail below.

2.2 Policies

The U.S. and EU have employed different strategies to support the research and development of a 2nd generation biofuels industry and expand the use of the more mature 1st generation biofuel market for use in the transport sector. The U.S. provides a wide array of producer incentives through substantial tax credits and explicit consumption mandates via the National Renewable Fuel Standard (RFS) which sets targeted levels of biofuel consumption. These are broken down by biofuel type according to the feedstock input used to produce the renewable fuel. The latest RFS requires the use of 136 billion liters of biofuels in 2022, which represents 7% of the nation's expected annual gas and diesel consumption in 2022 (EPA, 2010). Tax credits are \$0.45/gallon (\$0.12/liter) and \$1.01/gallon (\$0.27/liter) for cellulosic biofuels. There is also a small producer credit of \$0.10/gallon for small scale manufacturing. GHG reduction requirements are also being adopted.

As part of the EU's 2020 Climate and Energy Package, adopted in 2009, a Renewables Directive contains a 10% binding target for the use of biofuels in the transport sector by 2020. This means that biofuels must be used to meet 10% of the transport sector's total energy needs as opposed to the U.S. RFS which sets a fixed amount of biofuels that must be used. It also introduces a comprehensive set of sustainability criteria that biofuels must fulfill in order to be counted towards the target. The Renewables Directive highlights the necessity to "ensure the commercial availability of second generation biofuels." In order to implement the 10% by 2020 binding target, the European Commission created beneficial conditions for 2nd generation

biofuels by requiring that Member States give double weighting in their national biofuel obligations to biofuels originating from cellulosic feedstock sources. Excise tax exemptions for biofuels produced or blended in European countries have been introduced at various levels up to 100% by most Member States although, with the exception of Germany, they don't distinguish between 1st and 2nd generation biofuels.

The policies adopted by the U.S. and EU discussed above and additional support measures are summarized in the table below. A more in-depth discussion of policies employed can be found in Eggert, et al. (2011) and IEA (2010b).

Table 2.2: Summary of policy measures in place for biofuels

	<i>Consumption standards</i>	<i>Tax credits</i>	<i>Tariffs</i>	<i>R&D support</i>	<i>GHG standards</i>
U.S. ¹	RFS, levels inc. annually	\$0.45/g (1 st gen.) \$1.01/g (2 nd gen.)	\$0.54/g+2.5% appx. 30% total	Yes	Planned
EU ²	Blending requirements, 10% (2020)	Yes	Yes	Yes	Planned

1. The U.S. is the only country with separate mandates and tax credits for cellulosic biofuels.

2. Level of tax credits/exemptions vary by country.

The ensuing analysis will examine how the U.S.'s RFS and the EU's blending mandate may affect how oil resource owners' manage their stock and what their reactions might mean for global warming over the next several decades. First, we will look at the existing economic theory regarding the optimal use of these non-renewable resources.

3 Theory of exhaustible resources

The theory of the optimal use of non-renewable resources has been well developed with seminal ideas contributed by Hotelling (1931). Several subsequent applications have since been developed and findings contributed, particularly in the '70s. Since the reference models are derived from perfect competition and monopoly market structures with fixed marginal extraction costs, only the results of the theory that relates to these two particular scenarios will be addressed.

3.1 Perfect competition

The firm's problem, when facing decisions about how to optimally extract a non-renewable resource, is to maximize their net present value of profits obtained from the extraction of the resource while taking the market price as given. This comes from the assumption that each of the firms are too small to influence the market. Optimal control theory can be used to examine the intertemporal allocation of a known, finite stock of non-renewable resource and arrive at a set of dynamic and static efficiency conditions used to derive Hotelling's Principle.

With P_t as the price and c as the constant marginal extraction cost, the firm maximizes the objective function $\int_0^T [(P_t - c)R_t]e^{-rt}dt$ with respect to R_t , the rate of resource extraction, subject to the following constraints: $S_0 = \int_0^T R_t dt$, $\dot{S} = -R_t$ and $R_t \geq 0$. S_0 represents the total available stock of resource at $t = 0$ and $\dot{S} = \frac{\partial S}{\partial t}$, i.e., the change in stock over time which is equal to the resource extraction. The dotted variable form is used to represent time derivatives throughout the paper. The first constraint ensures cumulative extraction is not greater than the initial resource endowment.

The current value Hamiltonian, $H^c = (P_t - c)R_t - \lambda_t R_t$, yields the following first order conditions:

$$\frac{\partial H^c}{\partial R} = (P_t - c) - \lambda_t = 0 \quad (1)$$

$$\dot{\lambda} - r\lambda = -\frac{\partial H^c}{\partial S} \quad (2)$$

From (1), we can see that the price less the extraction cost per unit, i.e., the resource rent, is equal to the current value shadow price on the stock of the resource, λ_t . From (2), since the stock does not enter into the current value Hamiltonian equation, we know that this resource rent should grow over time at the rate of interest, resulting in the following Hotelling Principle for the optimal price path for a competitive firm with constant marginal extraction costs:

$$\frac{\dot{p}}{p-c} = r \quad (3)$$

This can also be thought of as the no-arbitrage principle, which may be more intuitive. It implies that at any given point in time, the resource owner should be indifferent between extracting an additional unit of the resource and investing the proceeds in the market to earn the rate of interest, i.e., the opportunity cost of not extracting, or leaving that unit of resource in the ground and extracting the following period at a price that has grown by the rate of interest. Once the price path is established, one can use the resource constraint to derive the terminal extraction period and initial price. The competitive firm will take the price path as given and use it to determine their optimal level of extraction/supply per period.

3.2 Monopoly

A monopolist has market power and the ability to set prices. They maximize the net present value of profits by choosing an optimal extraction and price path, taking into consideration that the market price is a function of the level of resource they choose to extract, i.e., $P_t(R_t)$. The problem is to maximize $\int_0^T [(P_t(R_t) - c)R_t]e^{-rt} dt$ with respect to R_t , subject to the same constraints listed in the competitive firm's problem while.

The current value Hamiltonian $H^c = (P_t(R_t) - c)R_t - \lambda_t R_t$ yields the following first order conditions:

$$\frac{\partial H^c}{\partial R} = \frac{\partial P_t}{\partial R_t} R_t + P_t - c - \lambda_t = 0 \quad (4)$$

$$\dot{\lambda} - r\lambda = -\frac{\partial H^c}{\partial S} \quad (5)$$

From (4) we can see that net marginal revenue is equal to the current value shadow price on the stock of the resource. Again, from (5), since the stock does not enter into the current value Hamiltonian, we know that this net marginal revenue should grow over time at the rate of interest. Let m denote marginal revenue. Then Hotelling's Principle for a monopoly exhaustible resource owner with constant marginal extraction costs can be expressed as

$$\frac{\dot{m}}{m-c} = r \quad (6)$$

If this result is not satisfied, then some marginal reallocation of the resource extraction between time periods with different present value of net marginal revenues would increase the present value of profits.

Marginal revenue, or $\frac{\partial P_t}{\partial R_t} R_t + P_t$ in (4), can also be written as a function of the price elasticity $m_t = P_t \left(1 + \frac{1}{\varepsilon(R_t)}\right)$.

Let $\gamma_t = 1 + \frac{1}{\varepsilon(R_t)}$ and ignore extraction costs. By differentiating $m_t = P_t \gamma_t$ we obtain $\frac{\dot{m}}{m} = \frac{\dot{P}}{P} + \frac{\dot{\gamma}}{\gamma}$ which can also be expressed, using (6) and disregarding extraction costs, as

$$\frac{\dot{P}}{P} = r - \frac{\dot{\gamma}}{\gamma} \quad (7)$$

Equation (7) can be used to evaluate how the role of elasticity of demand influences the monopoly's extraction path. A monopolist facing a constant elasticity of demand function, so that $\dot{\gamma} = 0$ and price is proportional to net marginal revenue, will follow a price path that grows at the rate of interest exactly as the perfectly competitive firm. Therefore, a monopoly resource owner facing a constant elasticity of demand will follow an optimal extraction path. In order to evaluate the impact of a variable elasticity of demand, we must know how the elasticity changes as the resource extraction changes over time. Taking the time derivative of γ_t gives us

$$\dot{\gamma} = -\frac{\dot{R}}{\varepsilon(R)^2} \frac{\partial \varepsilon}{\partial R}.^3$$

³ Using $\gamma_t = 1 + \frac{1}{\varepsilon(R_t)}$, $\dot{\gamma} = \frac{\partial \gamma}{\partial R} \dot{R}$ and $\frac{\partial \gamma}{\partial R} = -\frac{1}{\varepsilon(R)^2} \frac{\partial \varepsilon}{\partial R}$.

We know that $\dot{R} < 0$ since marginal revenue decreases with output and the only way for marginal revenue to rise at the rate of interest while the resource is being extracted is for the quantity supplied to decline over time. Therefore, the sign of $\dot{\gamma}$ can be determined directly from the sign of $\frac{\partial \varepsilon}{\partial R}$ leaving us with the following results using (7):

$$(i) \quad \text{If } \frac{\partial \varepsilon}{\partial R} > 0, \text{ then } \dot{\gamma} > 0 \text{ and } \frac{\dot{p}}{p} < r$$

$$(ii) \quad \text{If } \frac{\partial \varepsilon}{\partial R} < 0, \text{ then } \dot{\gamma} < 0 \text{ and } \frac{\dot{p}}{p} > r$$

In case (i), demand elasticity is increasing as demand trends towards saturation and this results in a higher price and smaller production initially compared to the competitive market. The monopolist is able to take advantage of the more inelastic demand in the earlier periods and charge higher prices. This is why the monopolist resource owner is commonly referred to as the 'conservationist's best friend.' The models used in this paper use a linear function of demand for transport fuels which inherently has the absolute value of elasticity increasing as the price increases and extraction falls, leading to the results concluded in (i). One can expect to see an increasing elasticity of demand as a result of the discovery and availability of good substitutes for the given resource, which increases as prices rise.

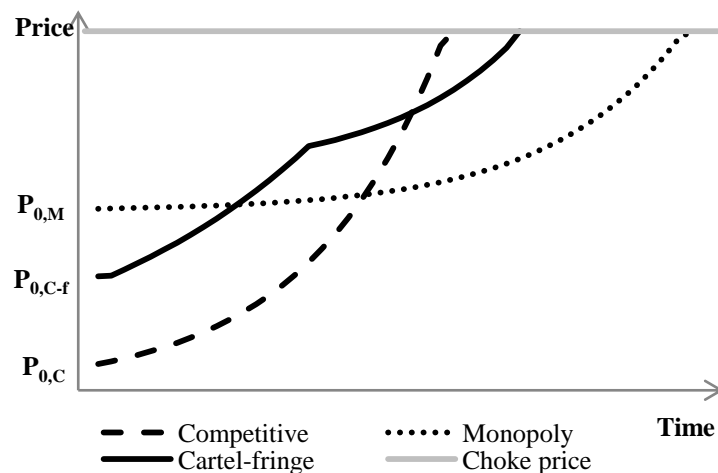
The previously derived results are confirmed and expanded upon by Stiglitz (1976) who shows that with positive extraction costs and a constant elasticity of demand the monopolist can still gain by reducing output in earlier periods relative to what is socially optimal.

3.3 Cartel-fringe

As Hotelling (1931), among others, have noted, the industrial organization of the world oil market is more appropriately viewed as somewhere in between perfect competition and pure monopoly. Salant (1976) modifies the conventional theory of exhaustible resources to account for a more accurate picture of the actual market structure: a dominant cartel (OPEC) with a competitive fringe (non-OPEC oil producers). He shows that in order for an equilibrium to exist in a dominant extractor model, the market will operate in two distinct phases. During the first phase, both the cartel and fringe operate and net price and net marginal revenue grow in the same proportion at the rate of interest according to Hotelling's Principle. This implies that the

elasticity of demand faced by the cartel is constant throughout this initial phase. At the end of the first phase, the competitive fringe exhausts its stock of resource. During the second phase, the cartel's net marginal revenue grows at the rate of interest and price grows at a smaller rate until its supply is exhausted, when the price path reaches the choke point. In this combined market structure, the initial price lies below the high monopoly price and above the low competitive price and the fixed world stock is exhausted more rapidly than under the monopoly, but less quickly than under competition. Figure 3.1 illustrates the characteristics of the optimal gross price paths for the different market structures, with the solid black line representing the cartel-fringe.

Figure 3.1: Comparison of price paths under different market structures



This paper evaluates the OPEC cartel as a monopoly resource owner. An analysis of the cartel-fringe market is not undertaken. Nevertheless, if the forthcoming analysis concludes that the various biofuel policies affect the perfectly competitive and monopoly markets in the same way, we can reasonably conclude that the results would hold in a combined market structure. However, if the markets react differently, the results are inconclusive and the cartel-fringe structure would be an interesting extension to this paper.

3.4 Empirical relevance

For the most part, empirical attempts to evaluate the validity of Hotelling's Principles fail to support the theory. One exception is Miller and Upton (1985) who test the theory using a

Hotelling Valuation Principle. The authors first point out that in a world in which the time path of exhaustible resources follows Hotelling's Principle; the value of the reserves in any currently operating, optimally managed stock depends mainly on current period prices and extraction costs, regardless of when the reserves are extracted. This is the essence of the Hotelling Valuation Principle – the average reserve value is equal to the current net price (market price less marginal extraction costs) and so it is independent of future prices and extraction costs. Letting V_0 represent the value of the reserves/stock, $V_0 = (P_0 - c) \int_0^T R_t = (P_0 - c)S_0$. This is because the growth in the price of the resource will be equally offset by discounting the value obtained in the future. The authors found that the estimated Hotelling values can account for a substantial portion of the variation in the market values of firms, that the results are robust and that the Hotelling measures are better indicators of the stock market value of petroleum properties than two widely cited publicly available measures of the value of reserves.⁴

However, a subsequent test produced different results for the authors and it, along with other studies conducted in the early '90s, suggest that the per unit valuation of reserves for oil and natural gas is only about half of current net prices (Krautkraemer, 1998). A survey of the empirical literature testing the relevance of the basic Hotelling model by Krautkraemer (1998) led him to conclude that it does not adequately explain observed resource prices and stock values. He notes that other features such as exploration for and discovery of new deposits, technological change and capital investment factors overshadow the finite availability of the resources as determinants of the observed prices and in situ values. Nevertheless, the models used to evaluate the research question are based on the Hotelling Principles derived in this chapter since it is the most suitable framework available.

3.5 Summary

Table 3.1 summarizes the results for the optimal use of non-renewable resources discussed in this chapter. In general, assuming a linear demand for transport fuels, one would expect that a monopoly resource owner would set a higher initial price, have a flatter extraction path and

⁴ The valuation indicators the results were compared to are the SEC Valuations and the Herold Appraisals. See Miler and Upton (1985) for more details.

later resource exhaustion date relative to a perfectly competitive firm. These results are revisited when the reference models are established.

Table 3.1: Hotelling's rules and the impact of the elasticity of demand

	<i>Perfect competition</i>	<i>Monopoly</i>
Hotelling's rule (constant extraction costs)	$\frac{\dot{p}}{p - c} = r$	$\frac{\dot{m}}{m - c} = r$
Hotelling's rule (zero extraction costs)	$\frac{\dot{p}}{p} = r$	$\frac{\dot{m}}{m} = r$
$\frac{\partial \varepsilon}{\partial R} = 0$		$\frac{\dot{p}}{p} = r$
$\frac{\partial \varepsilon}{\partial R} > 0$		$\frac{\dot{p}}{p} < r$
$\frac{\partial \varepsilon}{\partial R} < 0$		$\frac{\dot{p}}{p} > r$

We can now turn to the discussion of how policies designed to influence the market in which a nonrenewable resource owner operates may affect their resource extraction paths given the optimal conditions derived and discussed above. Of particular interest is how policies adopted to promote the use of 'greener' substitutes for 'dirty' fossil-based fuels in the transport sector may influence how an oil producer may opt to manage their stock of the resource.

4 Green paradox

Until recently, the supply-side dynamics of policies designed to promote the use of alternative fuels and their impacts on the extraction of fossil-based fuels have largely been ignored. The presumption has been that increasing the supply of a readily-available substitute would lower the demand and hence price of fossil fuels, thereby lowering the incentive to extract. However, this presumption assumes that oil resource owners don't react to these effects, i.e., that they are passive players in the energy market. However, if oil resource owners optimally extract their reserves, these owners will react to policies that affect the demand for their reserves and therefore adjust their output paths.

Sinn (2008) identifies the possibility that adverse supply side effects may arise if fossil-based fuel suppliers are threatened by reduced future prices brought on by a gradual greening of economic policies. Demand-reducing measures exert two countervailing effects on the current extraction path: (i) they reduce the incentive to extract today by depressing current prices and (ii) they increase the incentive to extract today because the anticipated demand and price decline that these policies generate in the future reduces the opportunity cost of the resource in situ.

Sinn (2008) notes that there are numerous ways in which governments and the public are implementing strategies to mitigate climate change, but they focus largely on reducing demand for fossil fuels through the development of alternative energy technologies and higher taxes on fossil fuels. Meanwhile the public debate is silent about the supply side. This is problematic since the development of the CO₂ concentration in the atmosphere depends on the extraction and use of the fossil-based fuel, a result of both demand and supply. Therefore, demand reducing measures will only be effective in mitigating climate change to the extent that they induce fossil-based fuel resource owners to leave their stock of fossil fuels underground or slow down the rate of extraction. Current levels of extraction must be reduced enough to allow the earth to maintain its natural capacity to absorb atmospheric CO₂, an ability that is becoming less effective as the atmospheric stock of GHGs continues to grow. The policies needed to mitigate climate change are those that make the fossil fuel extraction path flatter, meaning that

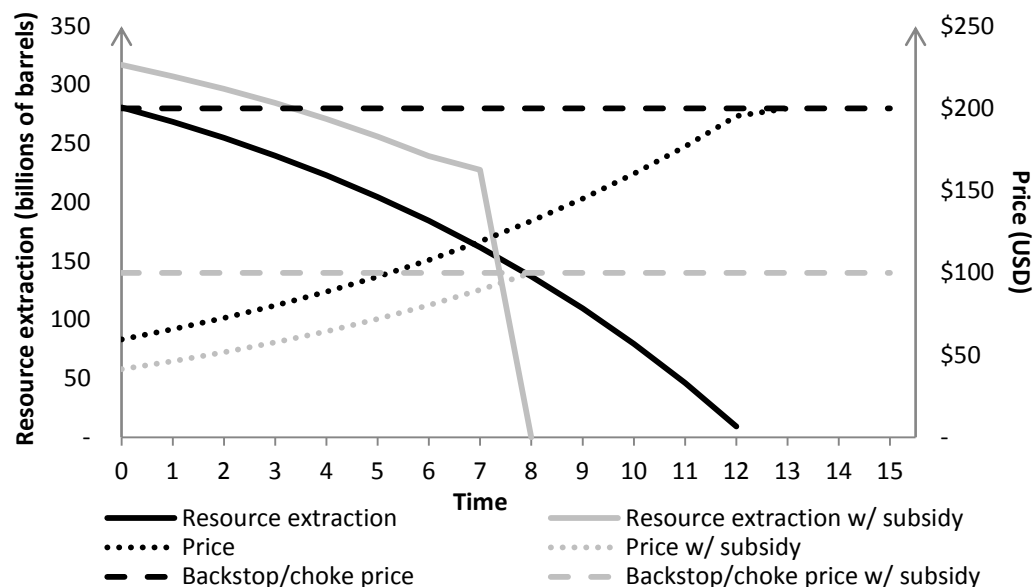
resource owners extract less today and more in the distant future. Demand reducing measures ability to induce this behavior is ambiguous.

Further, Sinn (2008) observes that if the suppliers of fossil-based fuels follow their extraction plans regardless of the decline in price, demand reductions by one country or a group of countries, such as those ratifying the Kyoto Protocol, will be useless. The reduced price will motivate other countries to increase their energy demand by exactly the same amount. This phenomenon is referred to as carbon leakage and can also occur if a country decides to leave some polluting sectors unregulated. Since energy created from the burning of fossil fuels cannot be decoupled from injecting more carbon into the atmosphere, with the exception of sequestration and afforestation, the accumulation of CO₂ in the atmosphere will not change. Introducing alternative methods of generating energy, such as transport fuels from biofuels, may depress the price of energy in the world markets and stimulate demand elsewhere. If they do not affect the extraction path of fossil fuel resources, alternative energy supplies will be consumed in addition to the energy contained in fossil fuels.

Sinn (2008) coined the phrase 'green paradox' to represent the situations where policy actions taken to mitigate climate change unintentionally incite fossil-based fuel resource owners to speed up their resource extraction path, i.e., the anticipated reduced demand effect outweighs any benefit of delaying extraction. As Sinn expressed, the existence of a green paradox shows that 'good intentions do not always breed good deeds.' He further illustrates examples that lead to this situation, focusing on the effects of an increasing cash flow tax rate or an ad valorem tax on carbon, but also notes how gradually greening demand policies, such as subsidizing the production of a clean energy substitute, can have similar adverse consequences in terms of speeding up global warming. Sinn's observations have sparked a collection of research, predominantly theoretical, to evaluate whether or not the paradox holds under more specific circumstances. Some of the findings are discussed below, but first let's examine an example of how subsidizing the production of a clean energy substitute may lead to the green paradox.

To illustrate the concept of the green paradox, assume there exists an expensive perfect substitute, referred to as the backstop, to an exhaustible resource. This backstop is available in unlimited quantities in the market at a price of \$200 per unit, the constant marginal cost of producing the backstop. Now, assume that the government decides that it wants to promote the use of this backstop and does so by offering to subsidize the producer's cost of making the good by \$100 per unit. Reducing the marginal cost of the backstop producer to \$100 (\$200 less the \$100 subsidy) and the market price at which the good will be available puts downward pressure on the maximum price that the non-renewable resource can receive in the market. The results of the implementation of this subsidy are to lower the choke price faced by the non-renewable resource owners, the price at which demand for their resource falls to zero. Assume that it is optimal to fully exhaust the stock of the resource and that the price path follows Hotelling's Principle and is increasing at the rate of interest. The reduced choke price encourages the exhaustible resource owners to lower prices and speed up extraction so that their entire resource stock is extracted before the market price reaches \$100. Applied to the global market for transport fuels, let oil and biofuels represent the exhaustible resource and backstop, respectively. One can see that if the production of biofuels is promoted to mitigate climate change via a subsidy payment to producers in order to make the renewable fuel more price competitive with oil, the optimal response by the oil producers could undermine the planner's initial objective.

Figure 4.1: Resource extraction and price paths with and without backstop subsidy



In the figure above, the black lines represent the case without any subsidies to the backstop. One can clearly see that the price under both scenarios stops increasing once it reaches the price of the backstop - \$200 in the case without the subsidy and \$100 in the case with the subsidy. This is also the point when the reserves are exhausted. Note also that the prices under both scenarios are growing at the same rate of interest according to Hotelling's Principle, an optimality condition derived in the previous chapter. The solid grey and black lines represent the resource extraction under the subsidy and no subsidy scenarios, respectively. The area under these curves is equal to the resource stock, the total amount of resource under the owner's control. Also note that the resource extraction falls to zero at the same time that price reaches the price of the backstop, which is significantly earlier in the case with a subsidy to the backstop producers. If the subsidy was implemented to mitigate climate change, we would have a case of the green paradox.

Changing the assumptions about extraction costs can lead to different conclusions about the green paradox. In fact, Gerlagh (2009) shows that increasing fossil fuel extraction costs as resources are depleted over time reduces the magnitude of the green paradox, while the paradox may vanish entirely if the backstop is considered to be an imperfect energy substitute.

Grafton et al. (2010) specifically analyze the impact of biofuel *ad valorem* production subsidies on fossil fuel resource owners extraction paths. They differentiate between a weak and strict green paradox, with the former existing when policies designed to reduce GHG emissions increase fossil fuel production. If the increased fuel production raises atmospheric GHG concentration levels, Grafton et al. (2010) refer to the outcome as a strict green paradox. The authors proceed to show that Sinn's (2008) argument for the possibility of adverse supply side effects in the context of green taxes is equally valid in the context of biofuel subsidies. However, among other results, they demonstrate how, with a linear demand function for fuels and supply function of biofuels, an increase in biofuel subsidies will delay the date of exhaustion of a resource stock in both competitive and monopoly markets. This occurs when extraction costs are positive, despite decreasing the choke price faced by the fossil fuel resource owners. An increase in biofuel subsidies will have no effect on the date of exhaustion if extraction costs are zero.

Withagen and van der Ploeg (2010) also explore the green paradox in the context of subsidizing renewable backstop technologies and, in contrast to Grafton et al. (2010), find that a backstop subsidy leads to an earlier exhaustion of non-renewables and to a faster rate of oil extraction. This occurs when the marginal extraction costs of non-renewables are less than the net cost of the backstop for any level of the stock implying that the non-renewable must be fully exhausted before the backstop takes over. This is similar to the results presented in [Figure 4.1](#). Furthermore, the authors propose that the green paradox prevails when the resource owner is a monopolist and backstop prices are relatively high compared to the initial marginal cost of extraction. In fact, they note that if there is a substantial concern for the environment, it would be better to tax the clean backstop in order to postpone exhaustion. However, if the backstop is eventually cheaper to supply than oil, subsidizing the backstop leads to a larger amount of reserves left in situ and the green paradox need not hold. The specifications of their model prohibit simultaneous use of the exhaustible resource and backstop.

In objection to the Bush administration's argument to focus resources on developing alternative energy sources versus ratifying a Kyoto type agreement with a limited number of participating countries, Hoel (2008) establishes a theoretical model to evaluate the effect of a reduction in the cost of a backstop technology on fossil fuels. He shows that carbon emissions are more likely to increase in the near future the higher is the elasticity of demand for the sum of the carbon resource and the substitute and the scarcer the carbon resource.

While the results obtained in these papers and others shed interesting light on the dilemma at hand, most are very theoretical and none attempt to explain whether or not the green paradox holds in the context of RFS and blending mandate policies. The analysis contained in the following chapters is an attempt to conclude whether the weak and/or strict green paradoxes exist when these specific policies are employed to promote the use of biofuels in the transport sector. To clarify, the term weak green paradox will be used in this paper to represent the case when fossil fuel production is increased in the earlier periods of the subsequent models analyzed. It does not necessarily mean that the resource exhaustion date is earlier than the case without government intervention. The strict green paradox follows the definition used by Grafton et al. (2010).

5 Reference model

The purpose of this modeling exercise is to compare and contrast the extraction path for oil, the non-renewable resource, including time until exhaustion, for the global transport sector under different policies adopted to promote the use of biofuels. Consequences of revised emissions paths are used to evaluate any impacts on the accumulation of GHG in the atmosphere and temperature changes. The results are then used to conclude whether or not the green paradox, in weak or strict form, is withheld. In this chapter, reference scenarios for competitive and monopoly markets in the absence of biofuel policies are reviewed. The following chapter looks at how the adoption of different biofuel policies affects the results of these reference scenarios. The first section within this chapter describes and discusses a set of comprehensive assumptions used throughout the paper in order to create the reference scenarios. Results of the reference models under perfect competition and monopoly market structures are then presented. The sensitivity of the results to some of the key assumptions made in developing the models is addressed in Appendix A.

5.1 Assumptions

5.1.1 Global demand for transport fuels

Functional form

The model assumes a linear demand function of the form $R_t = M - bP_t$, where R_t represents the supply of oil and P_t represents the price of oil. M and b are parameters derived from 2006-2010 actual volume and price data along with a review of estimated price elasticities. Consumption of fossil fuels is equal to the extraction. The constants, M and b , are derived given a price elasticity of demand, ε , and the base period consumption and price levels as follows:

$$M = R_t - \varepsilon R_t \text{ and } b = -\frac{\varepsilon R_t}{P_t}.$$

A characteristic of this demand function is that it ignores economic growth which would result in growth in demand; however, it is not completely disregarded. Instead, it is incorporated by treating the transport sector's use of oil as a larger share than its current actual share.

Price elasticity

The price elasticity was extrapolated by reviewing price and extraction path outcomes for competitive and monopoly market structures given current consumption, price and resource stock levels. The elasticity that resulted in a 2011-2015 price which could reasonably be expected to occur was then used to derive the parameters used in the demand function.

The long-run price elasticity for oil in industries and households (including services) varies between -0.1 and -0.6, with a weighted average of -0.37 for households. In the transport sector, the elasticity is thought to be on the lower end of the range due to fewer substitution possibilities compared to stationary oil (Aure et al., 2005). Substantial taxes and subsidies, particularly in non-OECD regions, puts additional downward pressure on the price elasticity. For instance, IEA (2010c) estimates that 37 large developing countries spent about \$557 billion on fossil fuel subsidies in 2008 with Iran, Russia, Saudi Arabia, India and China topping the list. Liu (2004) found the short-run and long-run price elasticities for motor gasoline in OECD countries to be -0.19 to -0.60, respectively, and compares his findings with results from other studies. Estimates vary across studies, most likely due to the specification of the models and data sets analyzed; however, empirical studies consistently find low values for short-term price elasticities that increase in the long-term. For instance, Pindyck (1979) found the long-run gasoline price elasticity to be -1.31 in the transport sector in OECD countries (Liu, 2004). I found that an elasticity of -0.25 calculated parameters in the demand function that justify a 2011-2015 weighted average gross price for the competitive and monopoly scenarios, with constant marginal extraction costs, of \$112.9 per bbl of oil. The weights are based on a blended market structure with OPEC acting as a monopoly and providing 39.9% of the supply from 2010 actual figures (IEA, 2011).

Base price and quantity

The 2010 base price of \$79.61/bbl used is the annual average price for the Brent blend, a crude oil marker for crude oil sourced from the North Sea (EIA, 2011a). Data for 2006-2009 actual world demand for crude oil was gathered from IEA's Oil Market Reports 2010 statistical supplement (IEA, 2010d). The 2010 figure is from IEA's February oil market report (IEA, 2011).

The percent of oil consumed by the global transport sector was 61.4% in 2008 (IEA, 2010a). Given that the share of oil consumed by transport is expected to grow as the wealth of the developing countries continues to rise and fossil fuel substitution possibilities continue to be limited in the sector more so than the electricity and industry sectors, a larger share is used in the model. In fact, the IEA predicts that the entire increase in world oil demand between 2009 and 2035 will come from non-OECD countries as OECD demand drops (IEA, 2010c). They also predict that the transport sector will account for almost all of the increase in oil demand during the aforementioned period, with China alone accounting for half of the global increase in oil used for transport (IEA, 2010c). Further, using a higher share compensates slightly for the lack of growth specified in the demand function. For these reasons, the models assume a long-term constant share of oil used by the transport sector of 75%, underscoring the importance of the development of transportation energy use in assessing future trends in demand for crude oil.

5.1.2 Other assumptions

Stock

The calculation of the total stock of crude oil available for use by the transport sector considers proven reserves, projected future increases in oil recovery of these proven reserves and undiscovered reserves. The volume of ultimately recoverable reserves is highly uncertain mainly due to difficulties in estimating how much oil was originally in place in the world and evaluating how much of the resource can be recovered profitably – which also requires assumptions about technology and costs of production inputs, among others. British Petroleum's widely cited figure for proven oil reserves for year-end 2009 is 1,331 billion bbl (BP Global, 2010). Proven reserves of oil are generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and geological conditions. The reserves include gas condensate and natural gas liquids (NGLs) as well as crude oil.

Reserve growth, increases in reserves that occur as oil or gas fields are developed and produced, are estimated to be 76.1% of proven reserves. This is based on a ratio of reserve growth to proven reserves for global oil and NGLs derived from a U.S. Geological Survey (USGS,

2000).⁵ Using current proven reserves, the ratio justifies a current reserve growth estimate of 1,015 billion bbl. Almost half of the increase in proven reserves in recent years has come from revisions to estimates of reserves in fields already in production as opposed to new discoveries (IEA, 2010c). Undiscovered reserves are estimated to be 1,073 billion bbl (USGS, 2000 and 2008) for a total of 3,421 billion bbl of ultimately recoverable reserves. This estimate falls within other contemporary ultimately recoverable reserve estimates ranging from 2,000-4,300 billion bbl (UKERC, 2009). Applying transports use at 75%, one can predict a stock of 2,566 billion bbl of conventional oil equivalent destined for use in the transport sector.

I have chosen to exclude unconventional fuel stock estimates including oil sands in Canada and Venezuela and Gas-to-liquid (GTL) and Coal-to-liquid (CTL) technologies. Canada and Venezuela oil sand deposits are projected to contain 1.0–3.6 trillion bbl of recoverable oil; however, the process of making liquid fuels from oil sands can generate up to 6.5 times the amount of GHGs per barrel of final product compared to the production of conventional oil. Well-to-wheel estimates project that the oil sand fuels emit 4-40% more GHGs than conventional oil (Charpentier et al., 2009). The higher emissions are primarily due to the higher energy requirements for extracting bitumen, a sticky, tar-like form of petroleum, and upgrading it into a synthetic crude oil. In addition, Withagen and van der Ploeg (2010) show that in the case of this ‘dirty’ and expensive backstop coupled with concern for the climate, it may be optimal to fully exhaust oil and gas reserves prior to using oil sands.

A more appropriate way to think of GTL and CTL may be as a backstop technology that will be adopted when transport energy prices approach the choke point where demand for conventional fuels falls to zero. Assuming that the cost to produce these fuels will be prohibitively high, especially if a carbon tax is implemented and applied to CTL production, justifies their exclusion. Further, we could argue that the cost to produce 2nd generation biofuels is cheaper in all periods analyzed and that it is likely more economical to use GTL in other sectors. The total size of the stock of these unconventional reserves is highly uncertain, but potentially as large as 2-3 trillion bbl may be economically recoverable (IEA, 2010c).

⁵ <http://pubs.usgs.gov/dds/dds-060/ESpt4.html#Table>

Time horizon

2006-2010 is considered the base period, i.e., $t = 0$, and actual resource price and extraction levels are used and fixed for the period. Results are analyzed for 48 five year periods with 2250 being the terminal year.

Discount rate

A constant 2% compounded annual discount rate for a period rate of 10.41% is used, implying period payments or foregone income is invested at the beginning of each of the periods. It is also assumed that the monopoly and competitive market firms face equal required rates of return which also reflect the social planner's discount rate. This allows us to directly compare the results derived for the two market structures.

Extraction costs

The reference model assumes constant marginal extraction costs which may be a reasonable assumption if one believes that technological development may directly offset any increased cost in extracting the more difficult to reach reserves. The models assume a fixed level of extraction costs of \$20/bbl. Major energy producing companies based in the U.S. incurred worldwide total lifting costs of \$11.51/bbl of oil equivalent (boe) in 2009, down \$1.19/boe, reversing an almost decade-long upward trend. Worldwide finding costs, which include exploration and development expenditures, were \$18.31/boe, for total worldwide upstream costs of \$29.81/boe (EIA, 2011b). Alternatively, Deutsche Bank estimated 2009 worldwide average production costs for 90% of the world's oil production to be \$6.60/bbl and in a 2007 study, estimate total costs, including capital and exploration costs, on average to be \$15.20/bbl (Karl, 2010). Note that the \$20 marginal extraction cost is more in line with the average costs found in the literature as opposed to a marginal cost, the theoretically correct cost to use. The actual marginal cost may be higher than \$20/bbl, although the upper ranges of the average values are skewed due to the inclusion of Canadian oil sands, which are not included in the calculation of total available stock in these models. On the other hand, they exclude refining costs.

Perfect competition model

Since solving the perfect competition model by maximizing profits requires given market prices for each period in question, a social planner's approach is taken throughout. The social planner's problem is to maximize the present value of social welfare over the time period analyzed by choosing the appropriate resource extraction and price path for a given period of time. The 2nd fundamental theorem of welfare economics which states that any Pareto optimal outcome can be achieved as a competitive equilibrium, under certain assumptions and conditions, allows us to solve the problems in this way. In other words, the optimal resource extraction and price paths derived from the social planner's perspective, *ceteris paribus*, also represents the profit maximizing extraction and price paths in a perfectly competitive market.

This model uses the inverse demand function $P_t(R_t) = \frac{M - R_t}{b}$. Define the social utility from consuming a quantity of the resource in each period as $U(R_t) = \int_0^{R_t} P(R_t) dR$, or $U(R_t) = \frac{M}{b}R_t - \frac{1}{2b}R_t^2$, an increasing and concave function of resource extraction. Note that by differentiating total utility with respect to R_t , we obtain $\frac{\partial U}{\partial R} = P(R_t)$ which states that the marginal social utility of resource use equals the price of the resource. Further, assume that the intertemporal social welfare function is utilitarian. Then the present value of social welfare over time can be expressed as $W = \int_{t=0}^T \left(\frac{M}{b}R_t - \frac{1}{2b}R_t^2 - cR_t \right) e^{-rt} dt$. This is the objective function that is maximized in the perfect competition models.

Methodology

The models are built in excel and the solver tool is used to calculate the optimal extraction and price paths for each of the scenarios.

The table below summarizes the value of the parameters calculated based on different elasticities assumed, along with implied choke price (equal to M/b) and $P_{t=1}$, the price for the 2011-2015 period. The parameters used for the reference models are highlighted in grey.

Table 5.1: Summary of parameters

ε	M	b	Choke price	Gross $P_{t=1}$	
				Perfect competition	Monopoly
(0.10)	129.514	0.148	\$875.71	\$71.63	\$451.47
(0.20)	141.288	0.296	\$477.66	\$51.50	\$251.32
(0.25)	147.175	0.370	\$398.05	\$47.68	\$211.33
(0.30)	153.062	0.444	\$344.98	\$45.52	\$184.70
(0.40)	164.863	0.592	\$278.64	\$42.26	\$151.46
(0.50)	176.610	0.739	\$238.83	\$40.70	\$131.57
(0.60)	188.384	0.887	\$212.29	\$39.80	\$118.36

5.1.3 Emissions and climate impacts

The conversion of oil consumption in the transport sector to carbon emissions requires the calculation of the carbon content of crude oil followed by its input into a model that calculates the carbon's accumulation in the atmosphere and impact on the temperature. The average theoretical kilogram (kg) of CO₂ per kg of crude oil is 3.15.⁶ A specific gravity (ratio of density of crude oil to CO₂) of 0.85, implies a conversion ratio of CO₂ kg/crude oil kg of 2.68.⁷ The CO₂ to carbon (C) factor, the ratio of molecular weight of CO₂ to C, of 3.67 (44/12) gives us 0.73 C kg/liter of crude oil or 116.21 C kg/bbl. This calculation is summarized in Table 5.2.

Table 5.2: Summary of crude oil carbon content

Crude oil	Liter	Barrel
Specific gravity (kg/liter)	0.85	0.148
CO ₂ kg/kg	3.15	0.296
CO ₂ kg/	2.68	426.12
CO ₂ to C factor	3.67	
C kg/	0.73	116.21

The basic methodology of converting emissions to the accumulation of GHG stock in the atmosphere and resulting temperature changes comes from a model created by Bjart Holtsmark, Statistics Norway, which is based on Höhne and Blok (2005) and includes calculations of the following effects: CO₂, methane (CH₄), nitrous oxide (N₂O) and sulfur dioxide (SO₂) emissions on concentrations; radiative forcing, the ability of heat radiation to escape through the atmosphere, and global-average surface-air temperature change. The business as

⁶ Energistatistikk 1998, vedlegg B

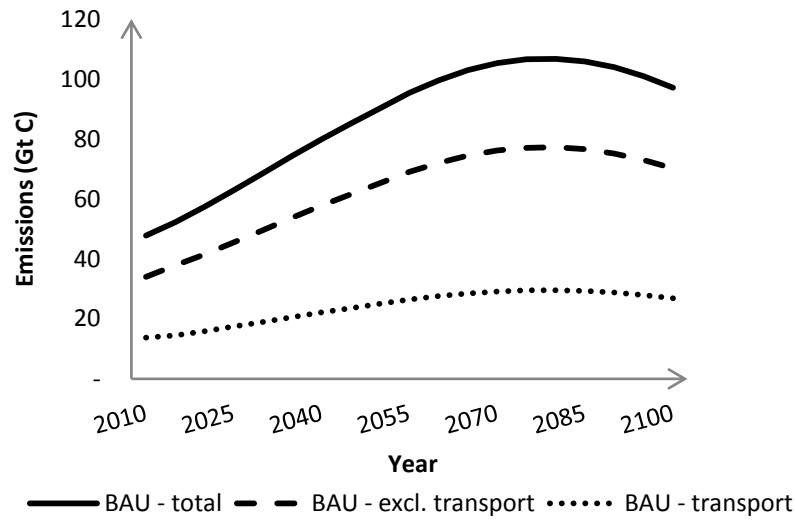
⁷ <http://cdiac.ornl.gov/pns/convert.html>

usual (BAU) scenario emissions used in the model is based on the IPCC's A1 scenario, characterized by rapid economic growth, a global population that reaches 9 billion by 2050 and rapid technological development that improves energy efficiency. This paper will only look at how the estimated change in the transport sector's carbon emissions due to the use of certain biofuel policies contributes to the stock of GHG's and temperature changes for the future periods.

The model uses an initial atmospheric GHG stock of 389.78 parts per million (ppm), the annual mean concentration for 2010.⁸ Since the BAU emissions in the model are not broken out by sector, in order to derive BAU emissions excluding the transport sector for the reference model, the transport sector's emissions are assumed to represent 27.7% of the total BAU carbon emissions. This share is based on the estimate of transport's base period (2006-2010) carbon emissions used throughout the models in this paper. The share is assumed to be constant throughout future periods in the climate model. These emissions are subtracted from the total BAU emissions in order to extrapolate 'reference' case emissions from all sources other than transport. The BAU transport emissions that are subtracted from the total BAU carbon emissions are replaced with the emissions calculated by the models used in this paper. The emissions derived from the policy scenarios are then compared to those generated by the reference case models. GHG accumulation and temperature changes are calculated from the various emissions paths that result from the optimal resource extraction paths generated from the reference and policy scenario models. BAU emissions are projected to increase through 2080 and then decline. The middle line represents emissions from all sectors other than transport. These are taken as given and are added to the emissions path generated by the reference and policy scenarios for the transport sector to discern any changes in the accumulation in GHGs and temperature changes.

⁸ Monthly average concentration of CO₂ in the atmosphere is published by the National Oceanic and Atmospheric Administration (NOAA) and republished by CO2Now.org, where the number was acquired on 2 March 2011. The data is measured at the Mauna Loa Observatory in Hawaii.

Figure 5.1: BAU emissions



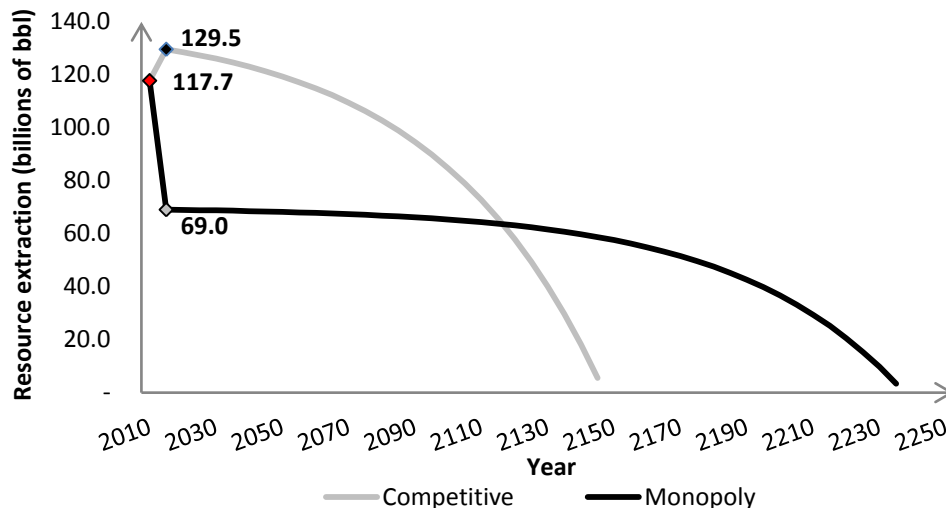
5.2 Results of reference models

The numerical results of the reference models are presented in the following table. Note that $P_{t=1}$ actually represents $P_{2011-2015}$ and is the meaningful result to review since $P_{t=0}$ is an actual, fixed value. Furthermore, T stands for the period in which the resource is fully exhausted. Reference scenario resource extraction and price paths are presented below the numerical results.

Table 5.3: Numerical results of reference models

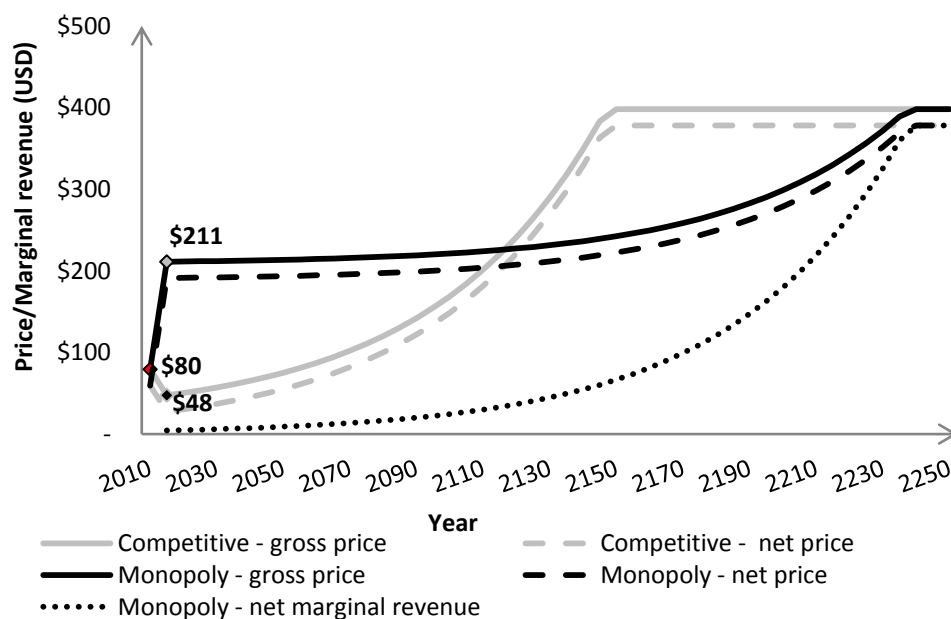
	<i>Perfect competition</i>	<i>Monopoly</i>
Gross $P_{t=1}$	\$47.68	\$211.33
$R_{t=1}$	129.5	69.0
T	27 (2141 – 2145)	45 (2231 – 2235)

Figure 5.2: Reference scenario resource extraction paths



The steeper resource extraction path in grey undertaken in the competitive market in grey compared to the monopoly in black is clear in Figure 5.2. This is a result of the monopoly's ability to use their market power to influence prices. They set higher prices, relative to the competitive firms, when demand is more inelastic, a characteristic of the linear demand functional form chosen. The monopolist's ability to strategically set prices above what is socially optimal is also evident in Figure 5.3.

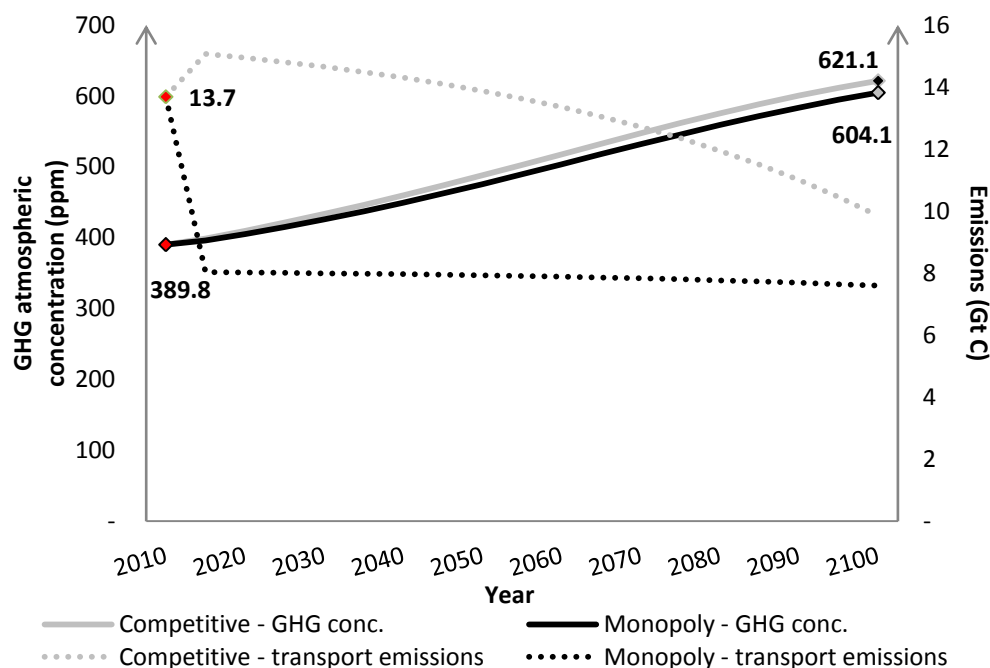
Figure 5.3: Reference scenario price paths



The optimal extraction of non-renewable resources requires prices to rise over time and the monopolist's optimal price path grows at a slower rate than that of the competitive firm due to the increasing elasticity of demand as price rises. This means that the monopolist will charge higher prices and reduce extraction in earlier periods compared to the competitive firm. The results presented above are consistent with the optimality conditions derived in the chapter 3. Notice that there are quantity and price corrections in the first period relative to actual values for the 2006-2010 period in both reference cases presented. This is to be expected since the perfect competition and pure monopoly markets represent the extreme boundaries within which the actual cartel-fringe market most likely operates. The direction of the corrections are consistent with what theory would lead us to predict.

The reference scenario's estimated carbon emissions and atmospheric GHG concentrations for the resource extraction paths discussed above are presented in [Figure 5.4](#). Focus is placed on the period ending 2100.

Figure 5.4: Reference scenario transport carbon emissions and GHG concentrations



While there is a dramatic difference in the optimal extraction path and emissions of a competitive versus monopoly resource owner, the difference in the accumulation of GHGs is

much more muted. By 2100, despite higher cumulative emissions of 94.4 Gt C in a competitive market, GHG concentration levels are just 17.0 ppm greater. As evidenced in the above figure, there is an extremely large lag between variances in current emissions and their accumulation in the atmosphere, a result of the non-linear relationship between emissions and radiative forcing. This relationship also has implications for the temperature effects.

Table 5.4: Reference scenario temperature changes

	<i>Perfect competition</i>		<i>Monopoly</i>	
	<i>GHG (ppm)</i>	<i>Temp. change (°C)</i>	<i>GHG (ppm)</i>	<i>Temp. change (°C)</i>
2030	433.2	1.21°	425.5	1.17°
2050	487.7	1.99°	475.3	1.91°
2075	561.4	2.87°	545.4	2.77°
2100	621.1	3.45°	604.1	3.35°

By 2100, the faster extraction path undertaken by the competitive firm leads to a temperature increase of just 0.10°C higher than that of a monopoly resource owner. This is because emissions that occurred as early as before 1900 are still affecting today's climate as they affect the decay of more recent emissions (Höhne and Blok, 2005). In fact, Røgeberg et al. (2010) recognize that the stabilization of global GHG emissions would have negligible impacts on the current speed of climate change. Even with a rapid reduction of emissions, global warming is likely to continue to occur for several decades. This message is consistent and apparent throughout the results presented.

6 Biofuel policies

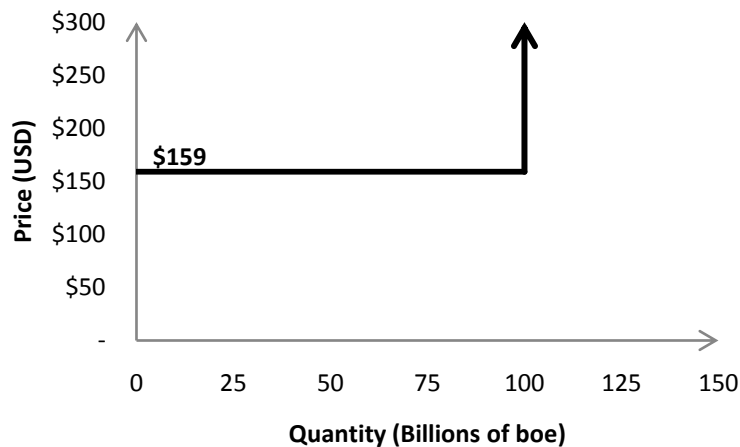
6.1 Modeling of biofuel policies

Before diving into the policy scenario models and results, some overarching assumptions that are made in the following analyses require attention. First, the models assume all the energy required to produce biofuels comes from biofuels and therefore fulfills any increase in the demand for energy needed to produce biofuels. This also means that the supply curve presented below is a net supply of biofuels. Furthermore, climate impacts of the various results assume that biofuels net emissions are zero as discussed in section 2.1. Climate impacts of the policies explored are discussed at the end of the chapter.

On the production side, no constraints on the resource owner's ability to react to biofuel policies are assumed, i.e., they are completely flexible in their production. This may be a strong assumption since, as observed by Krautkraemer (1998), the industry is capital intensive and it may be very costly to adjust extraction rates in response to a change in the price path. However, this exercise assumes that the policies are known far in advance and the model has a very long time horizon.

The same market price holds for oil and biofuels so that $P_t = (M - Q_t)/b$, where $Q_t = R_t + Y_t$, with Y_t representing biofuels production. In addition, biofuel production costs are assumed to be \$1.00/liter or \$159/boe, in line with current and future cost estimates presented in chapter 2. Further assume that up to 100 billion boe can be supplied at this cost, after which feedstock constraints in terms of total biomass available restrict any additional increase in production. This implies an infinitely elastic global supply curve for biofuels until producers reach a capacity of 100 billion boe. The 100 billion boe and constant marginal costs are justified given the existence of an abundant supply of cellulosic material and estimates of feasible bioenergy production presented by the IEA. This capacity is well within the expert assessments of the total potential energy available from biomass discussed in chapter 2. Further, in the presence of an RFS policy, as long as the marginal cost of biofuels is less than the price of oil, the supply of biofuels is decided entirely by the RFS.

Figure 6.1: Net supply of biofuels



The supply curve in [Figure 6.1](#) is an approximation of an actual supply curve that is more likely a gradually increasing function of quantity, convex in quantity until it reaches 100 bbl boe and capacity constraints prohibit additional increases in supply. Or the supply can be envisioned as presented, but with the vertical line gradually shifting out in conjunction with the increasing RFS. Note that it is implicitly assumed that the expansion of production capacity coincides with the volumes required to meet the RFS or blending mandate's standards. The assumption about the supply of biofuels is particularly important for designing the scaled up and prolonged RFS, relative to that which the U.S. has implemented, which is modeled and discussed in more detail in the following section.

6.1.1 RFS policy

In order to analyze the effect of a RFS-type policy on the fossil fuel owners' extraction path, some assumptions had to be made to incorporate the policy into the reference models. The policy is based on the U.S. RFS which specifies levels of biofuels to be used through 2022 (EPA, 2010). An annual growth in the standard of 5% following 2022 is assumed through 2090, after which the supply is considered to remain constant at 100.0 billion boe per period, consistent with the supply curve shown above. This is a conservative estimate of actual total available capacity compared to the range of biofuel production potential estimates and leads to results fairly consistent in terms of biofuels share of total transport fuel demand presented by IEA publications.

Actual data for global biofuels production was used for the 2006-2010 period (IEA, 2010d and 2011), adjusted for energy content based on a 2008 share of ethanol and diesel production of 77.1% and 22.9%, respectively (IEA, 2010b).⁹ The values put biofuel consumption at 1.5% of total global transport energy consumed (biofuel and crude oil) for the 2006-2010 period. The RFS is translated into a global policy by scaling up the U.S. policy and extending it to future periods per the assumptions highlighted above. The scaling up occurs by assuming that the U.S. provides a constant share of the total available global biofuels each period to fulfill the RFS requirements. A share of 45.3% is used based on 2010 actual data converted to boe (EIA, 2011c).

6.1.2 Blending mandate policy

The blending mandate policy used in the model is based on the 10% by 2020 objective adopted by the EU. This means that biofuels represent a required percentage share of total energy consumed by the transport sector, i.e., oil plus biofuels. The policy used in the model assumes a 5% blending target for the 2011-2015 period which increases by 2.5% per period. The blending mandate ultimately reaches 50% in period 19 (2101-2105), after which it remains constant at 50%.

6.2 RFS results

The numerical results of the RFS models are presented in the table below, along with the reference models output for comparison.

Table 6.1: Numerical results of RFS models

	<i>Perfect competition</i>		<i>Monopoly</i>	
	<i>Reference</i>	<i>RFS</i>	<i>Reference</i>	<i>RFS</i>
Gross $P_{t=1}$	\$47.68	\$21.79	\$211.33	\$204.81
$R_{t=1}$	129.6	138.0	69.0	69.4
T	27 (2141-2145)	42 (2216 – 2220)	45 (2231-2235)	Not exhausted
<i>Share of biofuels used in transport:</i>				
2020		3.5%		6.7%
2030		6.4%		12.0%
2050		14.1%		24.5%

⁹ A liter of ethanol contains 0.66 liters of gasoline equivalent. A liter of biodiesel contains 0.89 liters of diesel equivalent.

Compared to the reference scenario, implementing the RFS leads to lower initial prices and higher initial extraction in both markets, although the impact is much more pronounced in the competitive market. Also, results show that the exhaustion period is actually extended in both markets despite the higher initial extraction levels. More detailed figures of price and extraction paths are presented below and accompanied by a descriptive analysis of the intuition behind the results.

6.2.1 Perfect competition

Despite the delayed exhaustion date, the RFS induces competitive resource owners to speed up extraction in earlier periods, confirming that the weak green paradox holds. A lower initial price is set so that the net price may grow according to Hotelling's Principle before reaching a modified, reduced choke price, at which point the resource is fully exhausted.

Figure 6.2: Competitive RFS price path

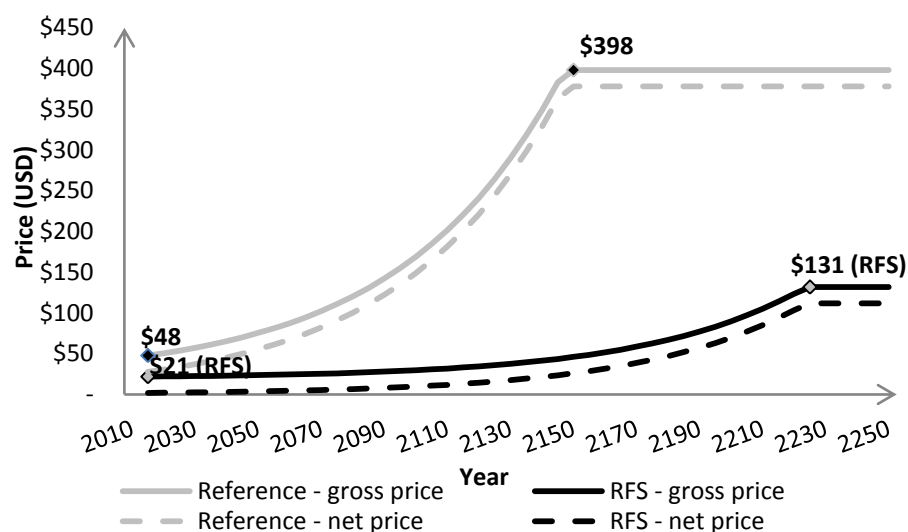
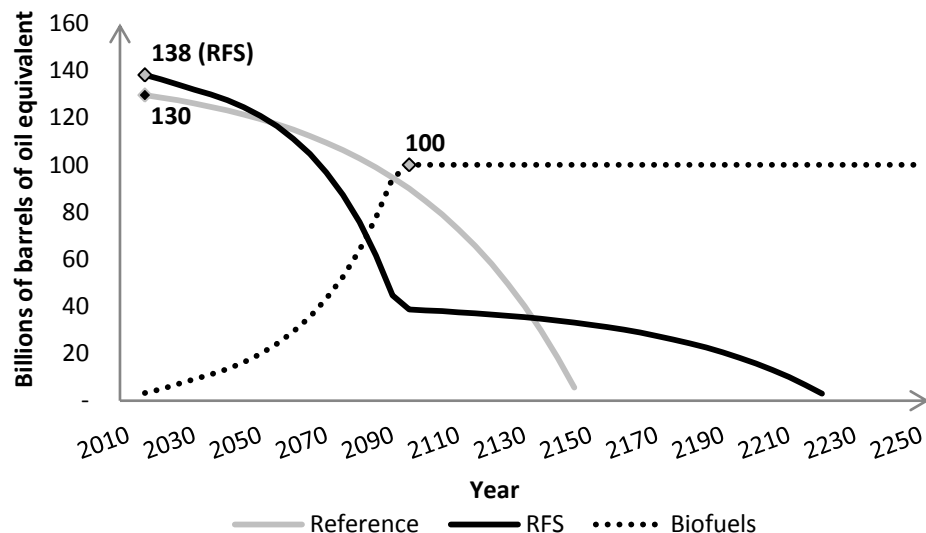


Figure 6.3: Competitive RFS resource extraction path and biofuel production



In the presence of the RFS, the resource owners will extract 138.0 billion bbl versus 129.5 in the first period with optimal initial prices reduced to \$21.79 versus \$47.68 in order to sell the additional supply. The RFS brings about higher extraction through 2050, lower extraction through 2130 and then higher extraction for the remaining periods until exhaustion, compared with the reference scenario. Note that the kink in the extraction path under the RFS scenario takes place when the targeted levels of biofuel use stops growing and remains constant at 100 billion boe. The higher initial extraction under the RFS can be thought of as the resource owner's anticipation of reduced demand for their product in future periods.

The optimal net price path grows at the rate of interest according to Hotelling's Principle and the resource is fully exhausted. In this instance, the presence of the RFS is the same as reducing demand for the resource in each period. The new choke price faced by the resource owners, the price at which the residual demand for transport oil falls to zero, is \$131.58 instead of \$398.05, derived from the demand for the non-renewable resource $R_t = M - bP_t - Y_t$, with $Y_t = 100$ and $R_t = 0$. The revised choke price and Hotelling's Principle leads to the following price path $P_t = (\$131.58 - c)e^{-r(T-t)} + c$. The initial price must be lower than the reference case to allow for the entire resource to be exhausted given the lower choke price. It is clear that the reduced demand for oil created by the gradually increasing RFS more than offsets the incentive to delay extraction today in exchange for higher prices in the future allowing us to

conclude that the RFS, as specified, leads to a weak green paradox when a competitive market is supplying the non-renewable oil.

Unfortunately, the results of this analysis are highly sensitive to the assumptions made about the RFS, stressing the dramatic effects that uncertainty about future policy can play in current extraction decisions. For instance, since biofuel consumption affects the price of the resource, if the quantity of biofuels is modeled so that it continues to grow to 141.9 or beyond, the optimal solution for periods of positive resource extraction/production is to produce at a level such that the market price will be equal to \$20, the resource owner's marginal cost of extraction. This is a solution we expect to see in a competitive market for resources that aren't subject to scarcity constraints. At biofuel standards above 141.9, the market price is below \$20 and it is no longer economical for resource owners to extract. This also results in an initial period of higher extraction than under the reference scenario; however, a portion of the resource stock will not be extracted.

6.2.2 Monopoly

Unlike the competitive market, despite a negligible increase in first period production, the existence of the RFS actually prompts a monopoly to reduce extraction in earlier periods, therefore allowing us to conclude that the green paradox does not hold in weak or strict form. Extraction and prices decline while the RFS increases over time until 2095, after which biofuel production remains constant (100.0 billion boe per period) as well as monopoly extraction (20.9 billion bbl per period) and prices (\$75.80). The monopoly will not extract the entire resource, leaving nearly 895 billion bbl in situ. Therefore, a monopoly producer does not follow a Hotelling Principle, but produces as though the resource constraint were not activated so that marginal revenue equals marginal cost during all periods.

Figure 6.4: Monopoly RFS gross price path

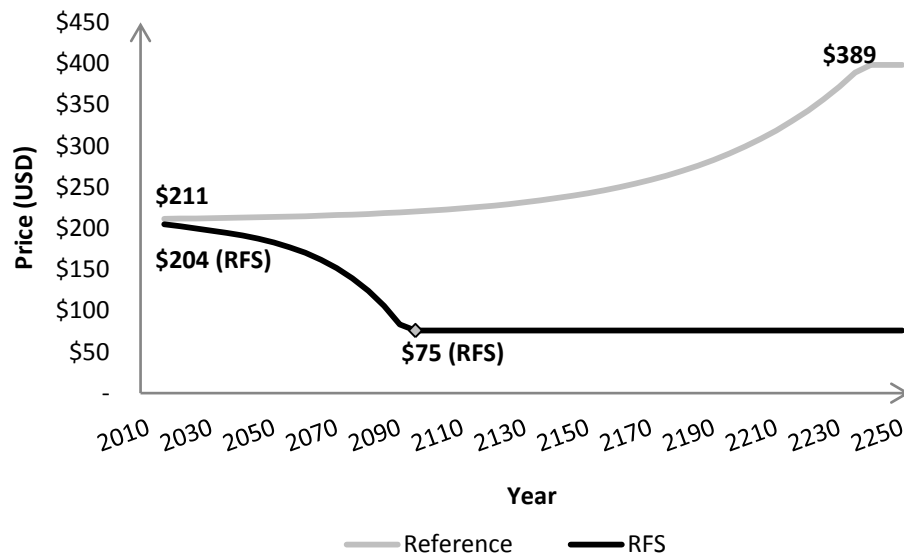
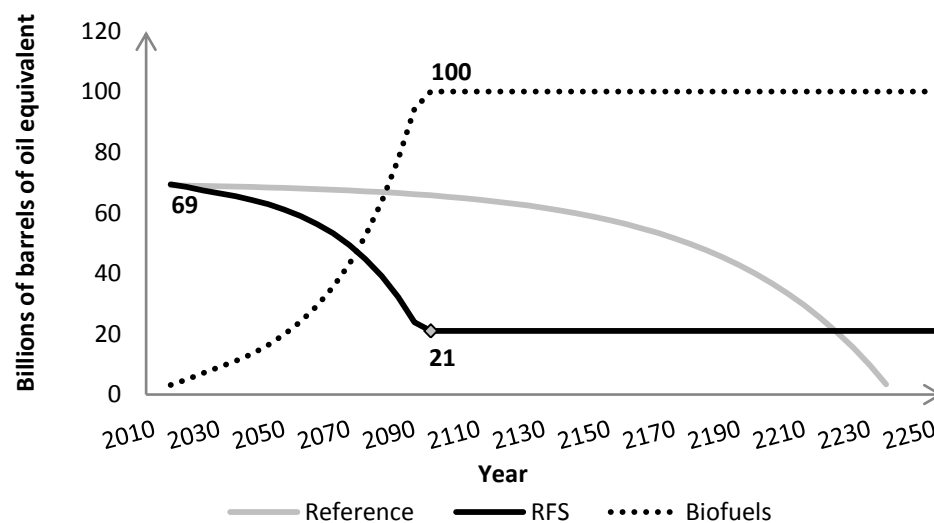


Figure 6.5: Monopoly RFS resource extraction path and biofuel production



The difference between the initial prices and quantities extracted in the first period between the reference and RFS cases are so microscopic and somewhat counterintuitive to the rest of the results that not much needs to be said about them other than that they are results solely related to the specification of the RFS. The development of the price and extraction paths paints a much more interesting picture. An important distinguishing feature of this model is that the monopolist can use its market power to influence prices by way of the quantity it

chooses to produce; however, it cannot control the amount of biofuels dumped into the market.

Hoel (1978) proves that a monopoly provider of a non-renewable resource is affected by the existence of a perfect substitute for the resource supplied by a competitive market and will react to the backstop in two phases. In the first phase, net marginal revenue will rise at the rate of interest until the price reaches its upper limit, the price of the backstop, at the end of the phase. This is a result of the monopolist not being able to sell resources at a price exceeding the competitive substitute price. However, it is assumed that he can sell as much of the resource as he wishes within the confines of demand when the price equals the cost of the backstop. This gives rise to the second phase which lasts until the resource is fully exhausted, during which the price is constant and equal to the cost of the backstop. The results show how a monopoly provider can take advantage of limit pricing in order to increase profits when threatened by a substitute product. Hoel (1978) further shows that the resource is extracted at a faster rate before exhaustion occurs when a substitute exists.

Unlike the problem presented by Hoel (1978), this monopolist is unable to influence when the backstop, e.g., biofuels, are introduced in the market by manipulating his price and extraction path which leads to significantly different results. We know from basic micro economic theory that at the profit-maximizing monopolist's choice of output, marginal revenue must equal marginal cost. When resource scarcity is a factor, an optimal extraction path requires that, in the presence of extraction costs, net marginal revenue grows at the discount rate according to Hotelling's Principle. However, as Weinstein and Zeckhauser (1975) show, when the constraint on the available stock is not binding, i.e., $S_0 > \int_0^T R_t$, the shadow price on the available stock, λ_t , equals zero and the net marginal revenue equals zero in all periods. Furthermore, marginal revenue must be non-decreasing over time. If marginal revenue is declining over time, a monopoly could increase profits by extracting more in earlier periods.

Given the specifications of the model, it is easy to show that marginal revenue is $m_t = \left(-\frac{1}{b}\right)R_t + P_t$ and price is $P_t = (R_t + Y_t - M)/-b$. Total differentiation of the equations

allows us to evaluate how R_t and P_t must change for a given change in biofuel consumption, Y_t , in order to fulfill certain assumptions about changes in marginal revenue over time. Total differentiation gives us¹⁰

$$dm = \left(-\frac{1}{b}\right)(2dR + dY) \quad (8)$$

$$dP = \left(-\frac{1}{b}\right)(dR + dY) \quad (9)$$

With a growing biofuel standard provided by the RFS, $dY > 0$. Equation (8) states that marginal revenue can only increase if $dR < 0$ and $|dR| > \left(-\frac{1}{2}\right)dY$, i.e., the decrease in R_t is more than half of the increase in Y_t . Equation (9) says that price can only be growing if the decline in R_t more than offsets the increase in Y_t so that the term in the second set of parentheses on the right hand of the equation is negative.

One can derive the maximum amount of resource a monopoly owner will produce during the periods when the biofuel standard, Y_t , is 100.0 billion boe using the equations for m_t and P_t and setting marginal revenue equal to marginal cost, \$20. This gives an extraction of 20.9 billion bbl per period. Any further increase in production would reduce marginal revenue below the cost of extraction. If marginal revenue were to grow, extraction must continue to decline from this point forward. Using this level of extraction for 2095-2250 one can work backwards to determine the total amount of resource that will be extracted during the entire period. Comparing the cases where marginal revenue is growing versus constant, the former requires a greater decline in extraction per period, implying a higher level of extraction in the earlier periods during which the RFS is growing. However, this leads to lower prices and profits during these periods compared to the case where marginal revenue is constant and the firm could increase profits by delaying extraction. Therefore, a profit maximizing firm would prefer to produce at a level that kept marginal revenue constant over time.

¹⁰ Equation (8) is derived as follows: From (10), $dm = \frac{\partial m}{\partial R}dR + \frac{\partial m}{\partial P}dP$, $\frac{\partial m}{\partial R} = \left(-\frac{1}{b}\right)$ and $\frac{\partial m}{\partial P} = 1$.

Using $dR = \left(-\frac{1}{2}\right)dY$ from (8) to calculate the change in extraction per period gives a maximum value for the entire amount of resource that will be extracted during the period of 1,670 billion barrels, much less than the total available stock. Furthermore, from (9) we can see that the price must be declining during periods of increasing biofuel production since the decrease in extraction is less than the increase in biofuel production. When biofuel production is constant prices are also constant. These results affirm the outcomes presented in the figures above, with declining extraction and prices while the RFS is growing.

Following the initial period of ratcheting up the biofuel RFS, during which the monopolist maximized profit by extracting at a rate such that $MR=MC$, one would expect the monopoly producer to adjust their production plan such that it follows the Hotelling Principle until the resource is fully exhausted. This is because with a constant level of biofuels in the market, the monopolist will maximize profit by gradually reducing production in order to sell at higher prices in the future to offset any effects of discounting. Given the large size of the remaining stock at this point, one would have to extend the model to include additional periods in order to see this adjustment. Furthermore, excel's solver tool is most likely not accurate enough to account for the infinitesimal discounting effects that far into the future.

The nature of the RFS used in this model leads to two main phases of extraction. First, while the RFS is increasing until 2095, resource extraction and prices will be declining. After 2095, prices and resource extraction will remain constant. These results are consistent with story presented in the graphs above and a result of a profit-maximizing monopoly producer choosing production levels such that marginal revenue equals marginal cost. Therefore, assuming that transport oil is provided by a monopolist, the adoption of an RFS policy will not induce the resource owner to speed up extraction so the green paradox does not hold.

6.3 Blending mandate results

The numerical results for the blending mandate scenarios are presented in the table below alongside the reference case results for comparison.

Table 6.2: Numerical results of blending mandate models

	<i>Perfect competition</i>		<i>Monopoly</i>	
	<i>Reference</i>	<i>Blending mandate</i>	<i>Reference</i>	<i>Blending mandate</i>
Gross $P_{t=1}$	\$47.68	\$37.29	\$211.33	\$209.03
$R_{t=1}$	129.6	128.6	69.0	67.4
T	27 (2141-2145)	41 (2211-2215)	45 (2231-2235)	Not exhausted
<i>Biofuels used in transport (billions of boe)</i>				
2020		6.8		5.3
2030		16.3		8.9
2050		27.9		16.0

In both markets, initial extraction is reduced and the time until resource exhaustion is extended, a climate friendly result. This can be thought of as a response by the producers to the use of biofuels being tied to their production levels. Every additional unit extracted has not only a direct effect on the price, but also requires a corresponding increase in biofuel consumption which reduces price even further. Therefore, it is reasonable to assume that the extraction path will be flatter under the blending mandate scenario due to this externality. The green paradox does not hold as the incentive to delay extraction to keep current prices higher more than offsets the incentive to extract today. This is not so unusual given that we would expect prices to increase and production to decline in the future, meaning that biofuel consumption, since it's simply a share of fossil-based fuels, will also decline in the future. This puts less pressure on the future residual demand for fossil-based fuels.

6.3.1 Perfect competition

Although the first period price and extraction in the presence of the blending mandate are very similar to the reference scenario, the optimal price and extraction paths in the presence of the biofuel policy develop much differently. In fact, the net price is growing at a decreasing rate over time while the blending mandate is increasing as opposed to a constant rate of interest like the reference scenario. This is most likely due to the fact that the benefit of delaying resource extraction further is declining as the mandated use of biofuels is increasing. In other words, the more that the mandate is expected to grow in the future, the larger the incentive to extract more today. Overall, current extraction is reduced and the resource is exhausted at a

later date than under the reference scenario. Note that the resource is fully exhausted when the price reaches the original choke point of \$398. A total of 1,373 billion boe of biofuels is consumed.

Figure 6.6: Competitive blending mandate price path

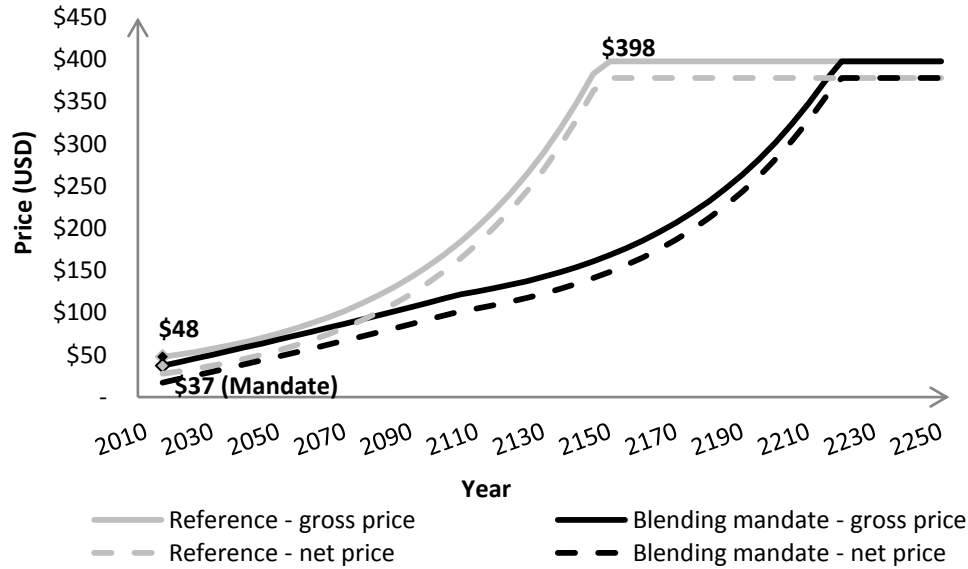
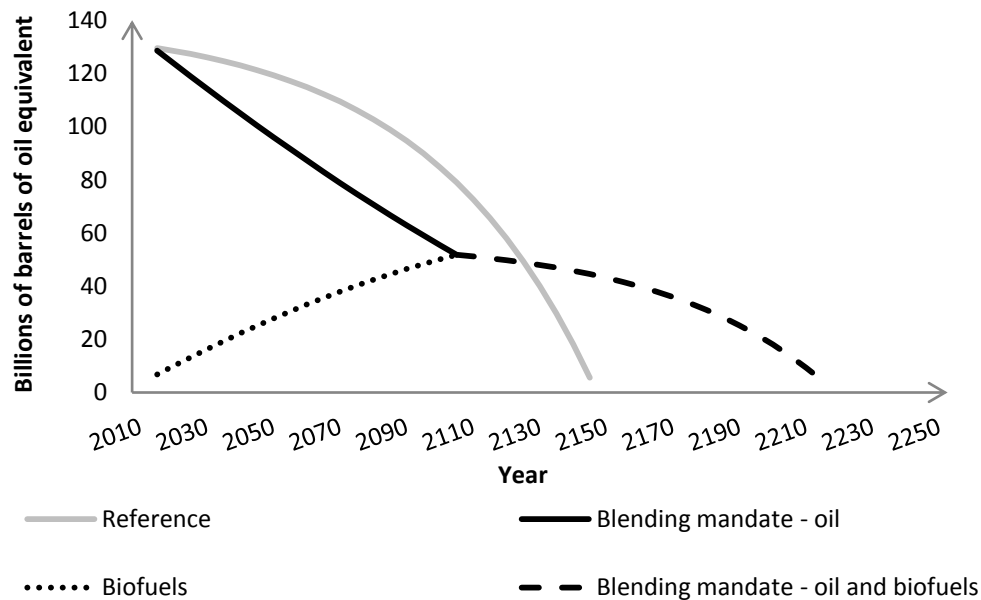


Figure 6.7: Competitive blending mandate resource extraction path and biofuel production



The following mathematical analysis supports the results presented above. Total demand for transport fuels, in the presence of a blending mandate, is $Q_t = R_t(1 + \alpha_t) = M - bP_t$, where

α_t represents the blending mandate requirement, expressed as a percentage of total energy consumption.

The above equation implies that $R_t = (M - bP_t)/(1 + \alpha_t)$ and, that $Y_t = \alpha_t R_t$. Further, let x represent the marginal cost of producing biofuels.

Using the social planners objective function described in Section 5.1.2 with modifications to account for the blending mandate, defined above, we can solve the revised maximization problem using control theory. The current value Hamiltonian becomes:

$$\mathcal{H}^c = \left(\frac{M}{b}\right) R_t(1 + \alpha_t) - \left(\frac{1}{2b}\right) (R_t(1 + \alpha_t))^2 - x\alpha_t R_t - cR_t - \lambda_t R_t$$

Maximizing with respect to R_t yields the following first order conditions:

$$\frac{\partial \mathcal{H}^c}{\partial R} = \left(\frac{M}{b}\right) (1 + \alpha_t) - \left(\frac{1}{b}\right) (R_t)(1 + \alpha_t)^2 - x\alpha_t - c - \lambda_t = 0 \quad (10)$$

$$\dot{\lambda} - r\lambda = -\frac{\partial \mathcal{H}^c}{\partial S} \quad (11)$$

From (11), since the resource stock does not enter into the Hamiltonian equation we know that

$$\frac{\dot{\lambda}}{\lambda} = r \quad (12)$$

Substituting $R_t = (M - bP_t)/(1 + \alpha_t)$ simplifies (10) to

$$P_t(1 + \alpha_t) - (x\alpha_t + c) = \lambda_t \quad (13)$$

From (12) we know that this modified resource rent should grow at the rate of interest over time. Compared to the basic Hotelling Principle followed in the reference scenario, this resource rent is further reduced by a fraction of the marginal cost of producing biofuels. Therefore, the existence of the biofuel mandate is similar to increasing the marginal extraction cost of the nonrenewable resource and we would expect to see an extraction path that is delayed relative to the reference scenario. Furthermore, (13) suggests that the effect of this increase in cost is enhanced as the blending mandate is increased. Taking the time derivative of (13) gives us

$$\dot{P}(1 + \alpha_t) + \dot{\alpha}(P_t - x) = \dot{\lambda} \quad (14)$$

Dividing (14) by (13) results in the following equation for the optimal price path

$$\frac{\dot{P} + \dot{\alpha}(P_t - x)/(1 + \alpha_t)}{P_t - (x\alpha_t + c)/(1 + \alpha_t)} = \frac{r}{(1 + \alpha_t)} < r \quad (15)$$

Dissecting equation (15) allows us to draw the following conclusions:

- (i) The effect of $(\dot{\alpha}(P_t - x))/(1 + \alpha_t)$ in the numerator depends on the dynamics of the blending mandate as well as the difference between the market price and the marginal cost of biofuels. If the blending mandate is constant, $\dot{\alpha} = 0$, or $P_t = x$, the term disappears from the equation. If the blending mandate is increasing like it is in the earlier periods of the model, $\dot{\alpha} > 0$ and one must look at the variance between the market price and the marginal cost of biofuels to determine the direction of the effect. For $P_t > x$, the mandate is increasing and the market price is greater than the marginal cost of producing biofuels, the term reduces the growth in the gross price path and calls for slower extraction of the natural resource. For $P_t < x$, the mandate is increasing while the market price is less than the cost of producing biofuels and the term prompts the growth in the price path and extraction to speed up. This could be because society is losing welfare by consuming biofuels that are expensive relative to the price of other substitutes available in the market, in this case, oil. It happens to be the case in the model that the market price is less than \$159, the marginal cost of producing a biofuel barrel of oil equivalent, for all periods during which the biofuel mandate is growing.
- (ii) The effect of $(x\alpha_t + c)/(1 + \alpha_t)$ in the denominator is essentially the same as increasing the constant marginal cost of extracting an exhaustible resource in the absence of a biofuel policy. The mandate has this effect because more biofuels, which cost money to produce, are used as the oil resource extraction is increased. This provides an incentive to reduce the resource extraction rate and extend the resource exhaustion date. It is also the case that, since the marginal cost of producing biofuels is greater than the marginal extraction cost, the higher the

blending requirement, the stronger incentive the resource owner has to delay extraction.

It turns out that the size of the effect of (i), when the blending mandate is increasing each period, is much smaller than the size of (ii) and the gap is growing as the blending requirement becomes increasingly larger. Therefore we would expect to see resource extraction and exhaustion delayed and the price growing at a decreasing rate while the blending mandate is increasing. When the mandate level stabilizes, the growth in the modified resource rent should also stabilize, although at a rate lower than the discount rate. This means that the rate at which the gross and net price grows will increase until the resource is fully exhausted. This is consistent with the results we see in figures above.

6.3.2 Monopoly

The monopoly producer's results are presented below. The monopolist produces such that marginal revenue equals marginal cost in the first period at a price of \$209. This price is kept constant and extraction is reduced while the blending mandate is increasing in order to prevent marginal revenue from decreasing. Once the blending mandate reaches 50% and remains constant, resource production and price remain constant. Less than the full stock is extracted, leaving 442.1 billion bbl in situ. A total of 1,401 billion boe of biofuels is consumed.

Figure 6.8: Monopoly blending mandate gross price path

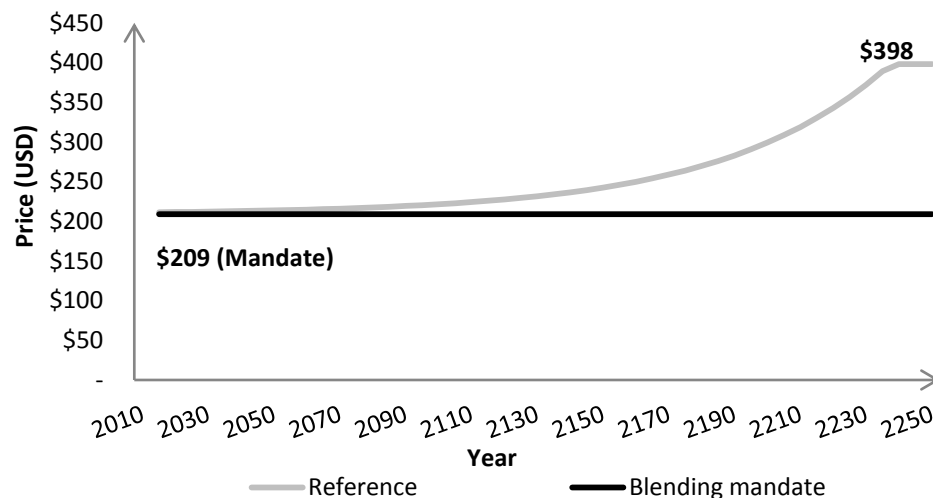
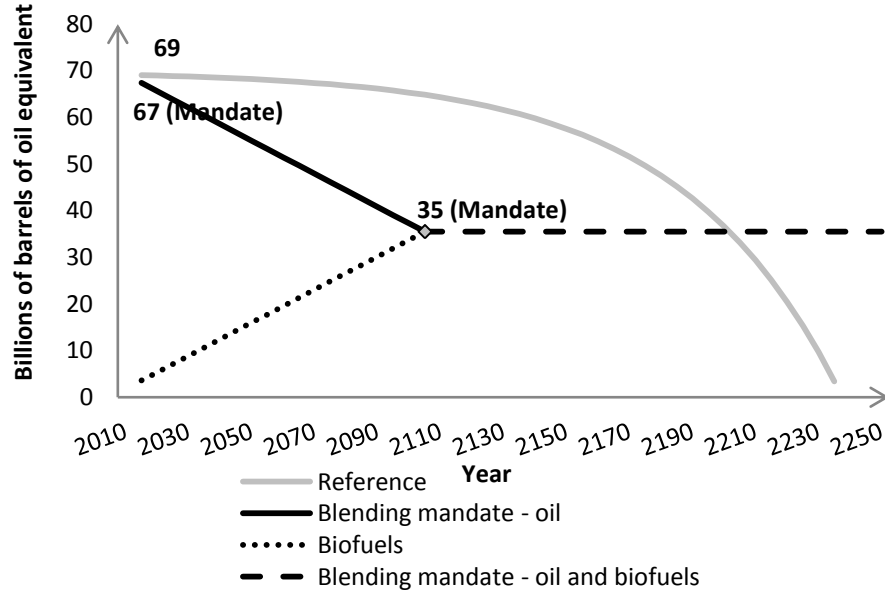


Figure 6.9: Monopoly blending mandate resource extraction path and biofuel production



We can calculate revised optimality conditions for the monopoly in the presence of a biofuel mandate. The revised profit function becomes $\pi_t = \left(\frac{R_t(1+\alpha_t)-M}{-b} \right) R_t - cR_t$ and the revised current value Hamiltonian is $\mathcal{H}^c = \frac{R_t^2(1+\alpha_t)}{-b} + \frac{MR_t}{b} - cR_t - \lambda_t R_t$ for the following revised first order condition $\frac{\partial \mathcal{H}^c}{\partial R} = \frac{2R_t(1+\alpha_t)}{-b} + \frac{M}{b} - c - \lambda_t = 0$. Substituting the revised demand function for the non-renewable resource, $R_t = (M - bP_t)/(1 + \alpha_t)$, and simplifying produces the following revised net marginal revenue equation equal to the present value of the shadow price on the resource stock:

$$2P_t - \frac{M}{b} - c = \lambda_t \quad (16)$$

The dynamic efficiency equation is still $\frac{\dot{\lambda}}{\lambda} = r$.

Since the resource is not fully exhausted according to the figures above, the shadow price on the resource stock must be zero and we would expect prices to remain constant over time and equal to $P_t = \frac{M+c}{2} = \$209$. This is exactly what we see in Figure 6.8. Using this price, the

amount of resource extracted per period can be calculated from the revised demand function for the resource, which is clearly declining as the blending mandate is increased.

If net marginal revenue, the left hand side of (16), is to grow at the rate of interest, extraction would have to decline over time so even less of the total resource stock would be extracted. More would be left in situ, but this can't be optimal since the market price is well above the marginal extraction cost so there are still profits to be made from extracting additional units.

To see how the price path would develop if the entire resource was exhausted, take the time derivative of (16) which gives us $2\dot{P} = \dot{\lambda}$. Dividing this expression by (16) and using the dynamic efficiency condition leads to the following expression to describe how the price path should develop

$$\frac{\dot{P}}{P_t - 1/2(\frac{M}{b} + c)} = r/2 \quad (17)$$

(17) says that a modified net price, which is much less than the net price in the reference case, should grow at half the discount rate. Gross price is growing at a rate that is less than half of the discount rate.

If the model was extended to include more periods and/or if the blending mandate was revised such that the resource constraint was activated and the revised net marginal revenue grew at the rate of interest, extraction and emissions paths would be extended relative to the reference scenario for the same reasons expressed in the competitive market solution.

This is confirmed by running the model with a blending mandate that is held constant following an increase to 10% in period 3. Resource extraction declines and prices increase over time, although at a much slower rate than the reference case, and the entire resource is extracted just as the price reaches the choke point. Given these results, we can conclude that the green paradox does not hold.

6.4 Climate implications

6.4.1 Perfect competition

The blending mandate extraction and emissions paths are below that of the reference scenario through 2100 and mitigate temperature increases, but no more than 0.06°C. On the other hand, the RFS emissions path starts above that of the reference scenario and decreases dramatically following 2050. This leads to slightly higher temperature increases relative to the reference scenario until 2080; however, the temperature variance peaks at 0.008°C. Therefore, we can say that the strict green paradox holds, but its effect is minimal and short-lived. By 2100, both the RFS and blending mandate policies are expected to result in only slightly mitigated temperature increases relative to the reference scenario. After 2100, since the entire stock of the resource is exhausted in all scenarios, the temperature increases begin to converge.

Figure 6.10: Competitive transport carbon emissions and GHG concentrations for reference and policy scenarios

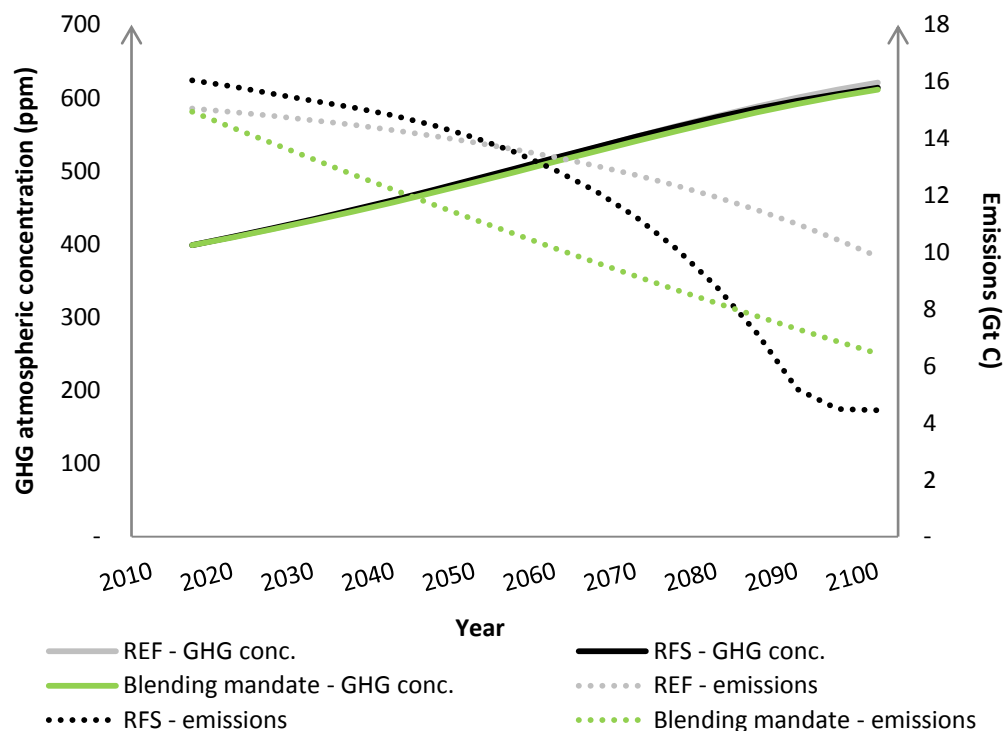


Table 6.3: Temperature (°C) impacts of biofuel policies in competitive market

	<i>Reference</i>	<i>RFS</i>	<i>Blending mandate</i>
2030	1.21	1.22	1.21
2050	1.99	1.99	1.97
2075	2.87	2.87	2.83
2100	3.45	3.42	3.40
2150	3.99	3.95	3.95
2200	4.05	4.05	4.06
2250	4.02	4.02	4.02

6.4.2 Monopoly

Despite emissions paths in both policy scenarios below that of the reference scenario, the accumulation of GHGs in the atmosphere is expected to be roughly in-line with the case of no policy intervention through 2100, resulting in temperature increase mitigation of a mere 0.04°C. Because the resource stock in the policy scenarios is not fully exhausted, cumulative emissions through 2250 are less than those in the reference scenario by 104.0 Gt C and 51.4 Gt C for the RFS and blending mandate cases, respectively. This leads to continued temperature increase mitigation beyond 2100, peaking at 0.12°C and 0.08°C for the RFS and blending mandate cases, respectively.

Figure 6.11: Monopoly transport carbon emissions and GHG concentrations for reference and policy scenarios

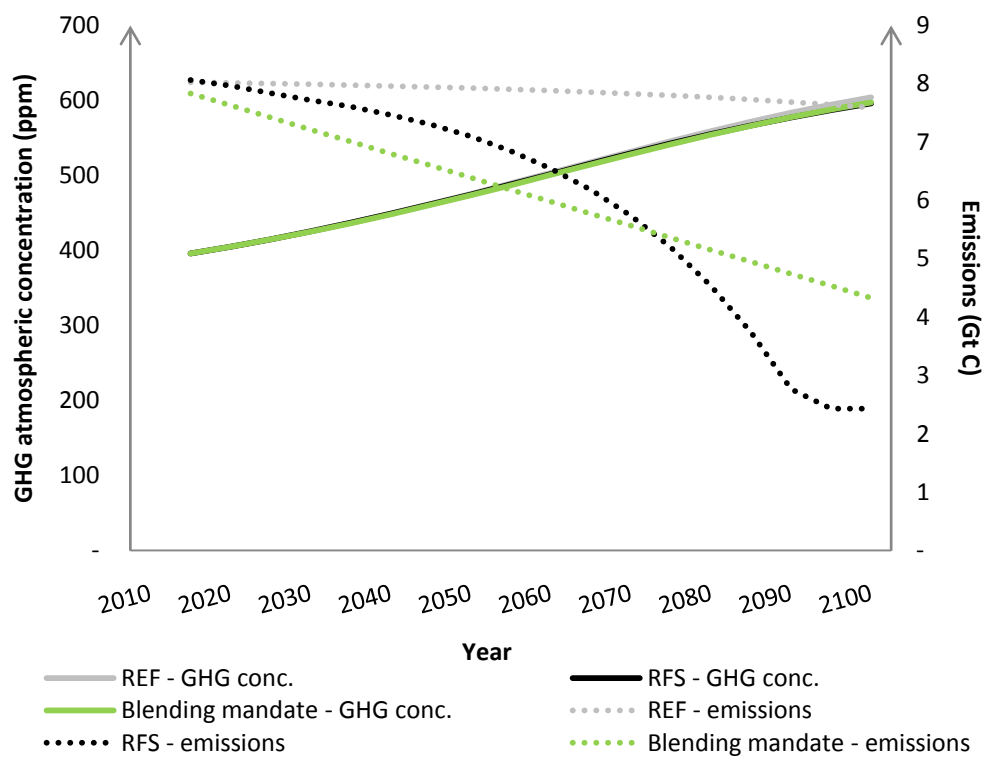


Table 6.4: Temperature (°C) impacts of biofuel policies in monopoly market

	<i>Reference</i>	<i>RFS</i>	<i>Blending mandate</i>
2030	1.17	1.17	1.17
2050	1.91	1.90	1.90
2075	2.77	2.76	2.75
2100	3.35	3.31	3.31
2150	3.92	3.84	3.86
2200	4.05	3.94	3.98
2250	4.03	3.94	3.99

7 Conclusions

This paper attempts to identify whether or not the green paradox is withheld when RFS or blending mandate biofuel policies are implemented to promote the use of the renewable fuel in the transport sector. The problem is addressed using a simplified model of the global transport market for energy, provided solely by fossil-based fuels made from oil and biofuels. Specifically, the effects of the RFS and blending mandate policies, implemented on a global scale, on oil resource owners' extraction paths are analyzed. A climate change model translates emissions from the use of the fossil-based fuels to the accumulation of greenhouse gases in the atmosphere and temperature implications.

The results of the models suggest that the weak green paradox only holds for the case when an RFS biofuel policy is employed and the non-renewable oil is supplied by a competitive market. The strict paradox also holds; however, it is short-lived and the impacts are minimal, with temperatures increasing by no more than 0.008°C relative to the reference case. The implementation of the RFS policy is the same as lowering the choke price faced by the resource owners. Because the optimal net price path continues to follow the rate of interest, they must lower initial prices and speed up extraction if the entire stock is to be exhausted.

It is clear that the green paradox does not hold in either the competitive or monopoly markets when a blending mandate policy is introduced. Resource extraction is delayed in both markets so we may also suspect to see delayed extraction of the resource when supplied by a cartel-fringe market. This is a result of the oil resource owners' efforts to avoid increasing the introduction of biofuels in the market which is tied to their level of production. The incentive to sell more in the present while the blending mandate is lowest is outweighed by the cost, in terms of a lower price, of increasing the supply of the resource in the market. While extraction paths are delayed in these scenarios, the reduced emissions in the earlier periods have a very small effect on estimated increases in the global temperature.

The outcomes imply that a blending mandate policy is a more effective tool for promoting the use of biofuels in the transport sector if intentions are to reduce near-term carbon emissions; however, we can't rely on the use of the renewable fuel to play a significant role in mitigating

climate change. Unfortunately, these results rely heavily on the specification of the reference model, the design of the biofuel policies and the climate change model. Therefore, outcomes should be taken with a grain of salt. Nevertheless, the resource owners' reactions to the biofuel policies follow intuitively and the direction of the temperature changes coincide with what we would expect to see given the revised emission paths.

While some estimates conclude that there is sufficient land available for the production of the levels of biomass feedstock necessary to produce enough biofuels to fulfill a large portion of transport energy demand, it's hard not to be skeptical given the rising population levels and food requirements. Furthermore, if 2nd generation biofuel cost reductions are not achieved and we must continue to rely on 1st generation biofuels to fulfill targeted levels of biofuel use, GHG emission reductions will be limited and mitigation of temperature increases will be even more negligible. In reality, these policies are only used by the U.S. and EU, so we can expect the use of biofuels to have an even smaller impact on future temperature increases than presented in this paper. These observations suggest that it may be better to focus attention on other strategies to mitigate anthropogenic climate change and/or towards creating adaptation plans for dealing with the consequences of what seems to be increasingly inevitable global warming.

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Appendix

A. Reference model sensitivity to assumptions

Elasticity

Altering the assumption about the elasticity influences the parameters of the demand function and ultimately the choke price. Increasing the assumed price elasticity, lowers the highest price the resource owner can charge forcing the owner to lower the earlier prices charged in order to sell the allotted stock before reaching the choke price and also leads to a shorter extraction period.

Figure A.1: Resource extraction paths for different elasticities

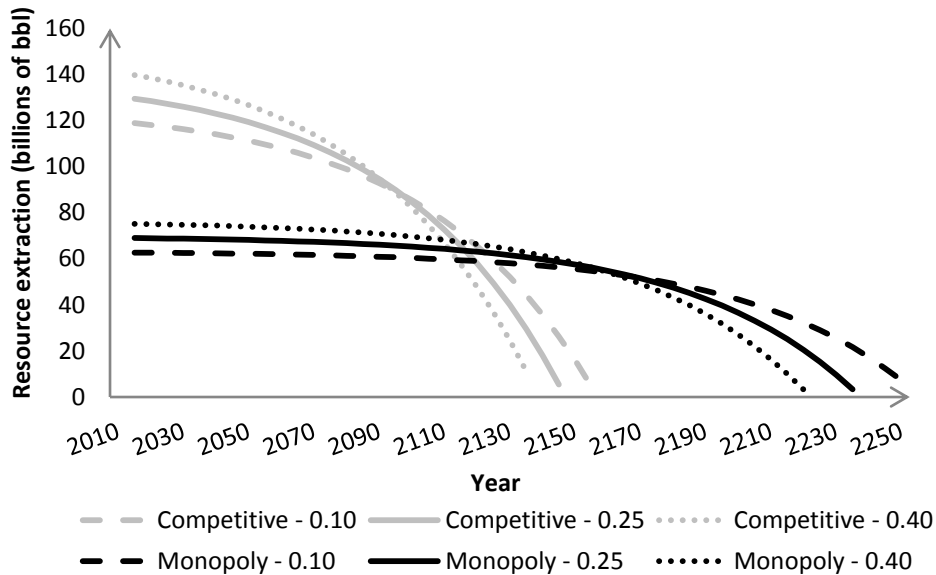
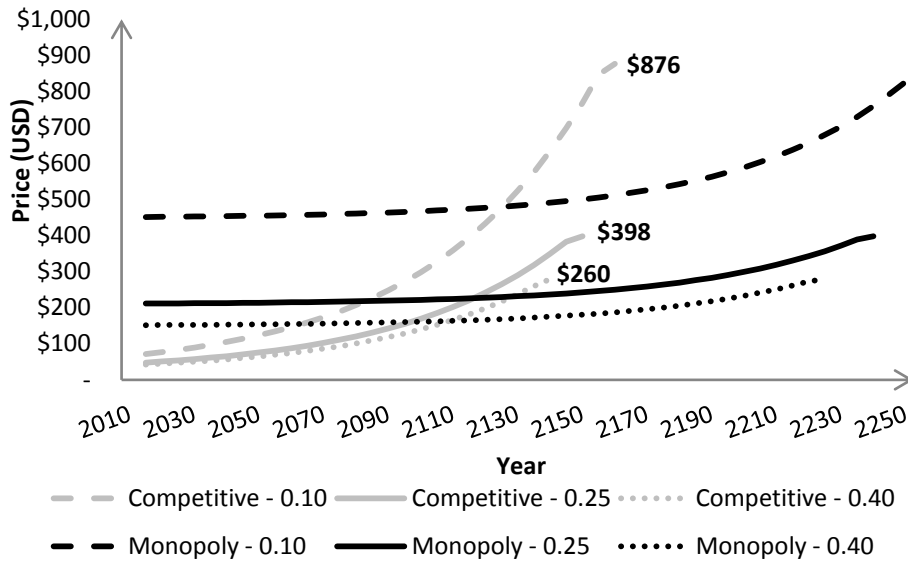


Figure A.2: Gross price paths for different elasticities



Base period price and extraction

For a given elasticity, $P_{t=0}$ and $R_{t=0}$ influence the definition of the M and b parameters in the demand function as they are derived from the equations which relying on the price and quantity levels. $P_{t=0}$ only influences the calculation of the parameter b , with $\frac{db}{dp} = \frac{\varepsilon R}{p^2} < 0$

for negative price elasticities. With the choke point, $\bar{P} = \frac{M}{b}$, an increase in $P_{t=0}$ will increase \bar{P} leading to a higher P_{2015} and an extended extraction path. It turns out that any change in the assumption about $R_{t=0}$ has offsetting effects on the M and b parameters and therefore does not affect the price or extraction path.

Stock

Increasing the available stock will lead to a lower P_{2015} and extended time until exhaustion if the entire resource is to be utilized by the time the choke price is reached.

Extraction costs

Increasing the level of extraction costs reduces the growth in price and delays the time until resource exhaustion. As discussed by Levhari and Liviatan (1977), for a resource with stationary demand and production costs that are an increasing function of cumulative extraction, it is possible that the stock of the resource will not be exhausted at the terminal point, implying

that the Hotelling scarcity rent would be equal to zero; however, the resource would still have a positive user cost (the difference between the price and marginal cost of extraction).

Figure A.3: Resource extraction paths for different levels of constant marginal extraction costs

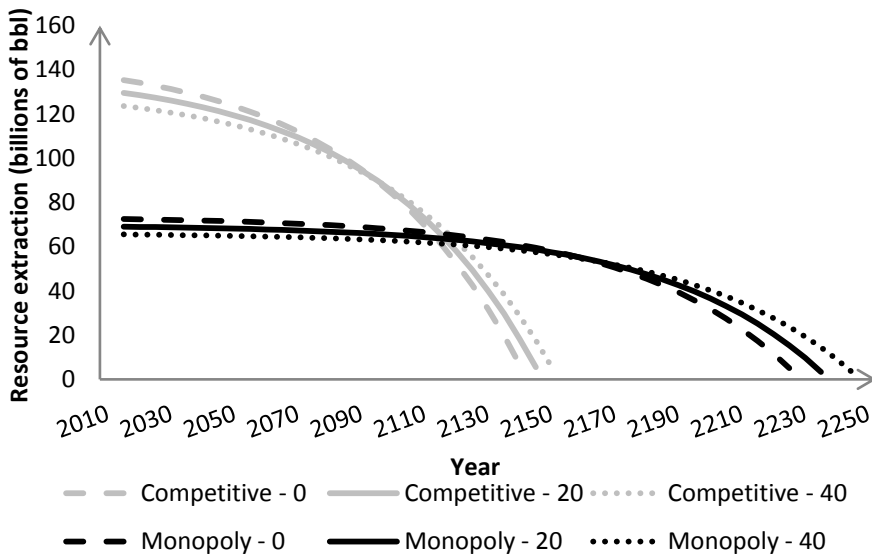
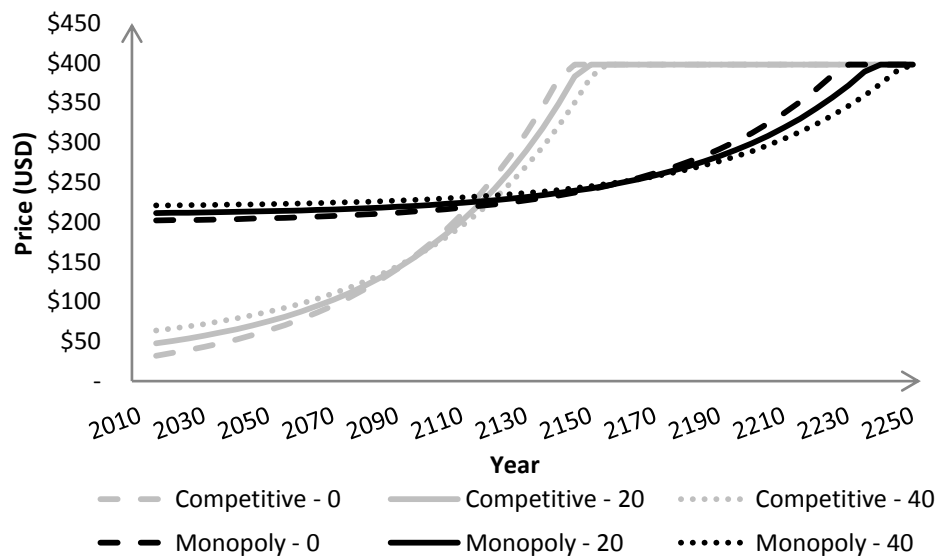


Figure A.4: Gross price paths for different levels of constant marginal extraction costs



Other considerations

Changing the percentage of oil consumed by the transport sector affects both the 2010 consumption figure used to derive the elasticity and the total available stock of resource

available to the sector. A change in this percentage will influence demand and stock in ways that will offset each other. For instance, increasing the percentage will increase the demand for oil by the sector in every period, but will be offset by an increase in the available stock to be used by the sector.

Table A.1: Summary of resource extraction and price path sensitivity to model assumptions

<i>Assumption (x)</i>	<i>$\frac{\partial P_{2015}}{\partial x}$</i>	<i>$\frac{\partial T}{\partial x}$</i>
Elasticity	-	-
$P_{t=0}$	+	+
$S_{t=0}$	-	+
Extraction costs	+	+